PNNL-20501

U.S. DEPARTMENT OF ENERGY

Prepared for the U. S. Department of Energy
under Contract DE-AC05-76RL01830

Using Electric Vehicles to Meet Balancing Requirements Associated with Wind Power

F Tuffner
M Kintner-Meyer

July 2011

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Richland, Washington 99352

Executive Summary

Many states are deploying renewable generation sources at a significant rate to meet renewable portfolio standards. As part of this drive to meet renewable generation levels, significant additions of wind generation are planned. Due to the highly variable nature of wind generation, significant energy imbalances on the power system can be created and need to be handled. This report examines the impact on the Northwest Power Pool (NWPP) region for a 2019 expected wind scenario. One method for mitigating these imbalances is to utilize plug-in hybrid electric vehicles (PHEVs) or battery electric vehicles (BEVs) as assets to the grid.

PHEVs and BEVs have the potential to meet this demand through both charging and discharging strategies. This report explores the usage of two different charging schemes: V2GHalf and V2GFull. In V2GHalf, PHEV/BEV charging is varied to absorb the additional imbalance from the wind generation, but never feeds power back into the grid. This scenario is highly desirable to automotive manufacturers, who harbor great concerns about battery warranty if vehicle-to-grid discharging is allowed. The second strategy, V2GFull, varies not only the charging of the vehicle battery, but also can vary the discharging of the battery back into the power grid. This scenario is currently less desirable to automotive manufacturers, but provides an additional resource benefit to PHEV/BEVs by theoretically doubling their capacity value to the grid.

Utilizing these two charging strategies, this report explores the potential of PHEV/BEVs to meet the entire additional energy imbalance imposed by adding 10 GW of additional wind to the NWPP. Vehicle travel patterns are based on data from the 2001 National Household Travel Survey data. Under certain market scenarios and penetration levels, the number of PHEV/BEVs in the total vehicle fleet provides a feasible resource for meeting the additional imbalance imposed by the wind generation.

The results indicate that the emerging electric vehicle fleet could make a substantial contribution toward meeting the new balancing requirements associated with the grid integration of growing wind technology deployment. To what degree this potential can be realized in the future will depend on the economics of the implementation and a viable and compelling business model, either for the individual electric vehicle owner, or a third-party service provider. The key findings are summarized as follows:

1. The study revealed a significant potential of the emerging electric vehicle fleet toward meeting some of the growing balancing services that grid operators will need to harness the fluctuations in the production of wind energy technologies. While a V2GFull operating mode may have some market acceptance barriers to overcome, V2GHalf would not be encumbered with these issues. V2GHalf strategies only require a modulation of the charging current without violating the users' desire to have the battery fully charged at a certain time. If about 13% of the existing light-duty vehicle stock (about 2.1 million vehicles) were PHEVs with a 33-mile electric range and applied V2GHalf charging strategies at home and at work, all of the additional balancing requirements of 3.7 GW could be provided by the electric vehicles. (See Table E.1).

2. The results indicate a strong relationship of the charging station availability throughout the day (referred to as "charging at work") on the total number of vehicles required to meet the balancing requirements. The results reveal a behavior of diminishing returns after the vehicle stock is offered a certain amount of charging stations at work. Almost 80% of the improvements by offering public

charging stations at work can be achieved with about 10% of public stations (i.e., a public to residential charging station ratio of 1:10).

3. A comparison between V2GFull and V2GHalf confirmed that the individual larger capacity that V2Gfull service offers to the grid (6.6kW=3.3kW – (-3.3kW)), which is theoretically double the capacity of V2GHalf (3.3kW), requires a smaller number of vehicles to meet the additional balancing constraints. The V2GFull service requires, on average, about 30 to 35% fewer vehicles than the V2GHalf approach, across all scenarios.

4. The size of the vehicle battery matters for supplying balancing services. For the home-only charging option, the larger battery (BEV) reduces the number of required vehicles in the range of 17% to 30% over that for a PHEV33, while for home and work charging options, the improvement potential is only between 7% and 10%.

5. The results are relatively insensitive to the charging level. A comparison between Level 1 and Level 2 charging revealed very little differences. This suggests that the apparent advantage of higher electricity demand of Level 2 charging (3.3 kW) compared to Level 1 charging (1.7 kW), does not reduce the number of vehicles to meet the balancing requirements in the proportion of the charging limits.

6. A limiting case was defined that postulated that all electric vehicles be available 24 hours per day – 7 days a week performing V2GFull services. This limiting case is identical to a distributed stationary energy storage system dedicated to perform balancing services. For this limiting case, a total number of about 560,000 vehicles (4% of light-duty vehicle stock) would be necessary with a Level 2 (3.3 kW) charging/discharging technology to provide all of the additional balancing services.

Table E.1. Population of Vehicles Required to Meet Additional Balancing Requirements

Charging type	**Battery Size Scenario**				
	Stationary Storage	**PHEV 33**		**PHEV 110 (BEV)**	
		Home only	**Home and Work**	**Home only**	**Home and Work**
V2GHalf	-	29.7 mill (180%)	2.1 mill (13%)	20.8 mill (126%)	1.9 mill (12%)
V2GHalf and V2GFull	-	21.8 mill (132%)	1.6 mill (10%)	17 mill (103%)	1.4 mill (8%)
V2GFull	0.6 mill (4%)	18.6 mill (113%)	1.4 mill (8%)	15.5 mill (94%)	1.3 mill (8%)

(Percentages are based on 16.5 million light-duty vehicles in NWPP)

Acronyms

ACE	Area Control Error
AC	alternate current
BEV	battery electric vehicles
EPRI	Electric Power Research Institute
MSE	mean-squared-error
NWPP	Northwest Power Pool
NHTS	National Household Travel Survey
PNNL	Pacific Northwest National Laboratory
PHEV	plug-in hybrid electric vehicles
V2GFull	vehicle-to-grid-full
V2GHalf	vehicle-to-grid half

Acknowledgement

The authors wish to thank Dr. Marcelo Elizondo and Dr. Chunlian Jin at the Pacific Northwest National Laboratory for their assistance in generating the balancing data used as a basis for the study. Without its availability, a realistic basis for the simulation would not have been possible.

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1.0 Introduction

Renewable generation sources are being deployed at a significant rate. The primary driver of the deployment comes from mandated renewable or alternative energy portfolio standards law in 36 states and the District of Columbia [Pew Center 2011]. Of all of the renewable generation sources, wind is expected to be most significant component of the new capacity, followed by other resources such as solar, some geothermal resource primarily on the western states, and biomass.

One challenge of wind and solar generation sources is the variability in the output [Lauby et al. 2009]. Lulls in the wind and clouds across the photovoltaic panel can significantly reduce the output of such generation sources. Conversely, a sudden gust of wind can create an excess energy output from the resource. These fluctuations can have significant impacts on the power system [Simburger and Cretcher 1983; Loutan et al. 2009; Makarov et al. 2009]. To stabilize and mitigate these fluctuations, flexible hydro units and combustion turbines are customarily utilized. Energy storage and demand response resources have been more recently discussed as a viable technology solution [Halamay et al. 2010; Ortega-Vazquez and Krischen 2009].

End-use loads can also be used to meet this balancing [Roscoe and Ault 2010]. The emerging electric vehicle fleet provides a significant resource that could be used to meet these balancing service requirements [Short and Denholm 2006]. Unlike traditional demand response schemes for air-conditioning, an electric vehicle has greater flexibility in its operating schedule, thus, lending itself to be used as a balancing resource. As long as the vehicle battery is fully charged at a specific time (usually in the morning), the vehicle owner would not be concerned about the actual period of charging. There is usually significantly more time left between the time the vehicle is plugged in and the time the battery is expected to be fully charged. This provides significant flexibility for load management strategies that would support the integration of variable renewable energy resources.

One method for providing balancing services is through electric vehicle charging that utilizes varying control of the charge rate in response to grid needs. Many approaches to this problem exist, including centralized and decentralized control schemes [Saber and Venayagamoorthy 2010; Han et al. 2010; Kintner-Meyer et al. 2009]. As part of the Grid-Friendly Charger technology development at the Pacific Northwest National Laboratory (PNNL), one such decentralized scheme was developed.

The PNNL Grid-Friendly Charger incorporates a charging method described as a "regulation-services" charging mode, or vehicle-to-grid half (V2GHalf) [Kintner-Meyer et al. 2009]. In this charging mode, local indications of grid stress, such as the alternate current (AC) frequency, are utilized to vary the charging rate for an electric vehicle. Utilizing this autonomous, decentralized control scheme, a population of electric vehicles can help meet the additional balancing services and variability in power generation caused by renewable generation sources.

In this paper, V2GHalf-based charging is simulated on a population of electric vehicles to determine the number of vehicles necessary to provide the additional balancing requirements associated with the introduction of about 10 GW of additional wind generation into the Northwest Power Pool (NWPP) in the United States. A previously published PNNL report generated the wind balancing signal utilized in this work [Kintner-Meyer et al. 2010]. The National Household Travel Survey (NHTS) data provided personal vehicle use patterns to investigate behavior of large populations of vehicles representative for the U.S. as a whole. Extensive simulations were performed given the driving patterns of U.S. light-duty vehicles and battery performance to meet the new balancing requirements. Furthermore, sensitivities with respect to the impacts of Level 1 versus Level 2 charging, *home* charging versus *home* and *work* charging, and the size of the vehicle battery (PHEV 33 versus EV with 110 miles range) were explored.

This report describes the results of these simulations and interprets the results in the context of estimating the number of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) necessary to meet all of the new balancing requirements as a consequence of the new wind installation.

The rest of this report is divided as follows: Section 2 describes the approach used in the simulation, including the underlying data sets and methodology. Section 3 presents a subset of the results from the different simulations. The report concludes with some general observations (Section 4) and a discussion on the significance and implications of electric vehicle charging to the renewable energy technology integration efforts.

2.0 Approach

Exploring the benefits PHEVs and BEVs may provide for renewable resource integration options can be best performed by means of simulations. These simulations investigate the impacts of different electric vehicle penetration rates, battery sizes, vehicle availability, and charging infrastructure availability on the overall results. For this study, all simulations were performed in the Mathworks MATLAB environment [Mathworks 2010].

2.1 Data

Proper investigation of the potential for PHEVs and BEVs in support of the integration of renewable resources required two data sources: 1) data sets representing the underlying power balancing signal or grid needs at a high contribution of renewable energy technology to the U.S. generation mix. This is a time series of power requirements about the 0-axis, requiring a balancing increment (in positive power direction) and a balancing decrement (in the negative power direction) to compensate for the variability in the wind output and for the forecasting errors of load and wind supply; and 2) underlying vehicle population availability and driving patterns which determine the state of battery charge when arriving at a charging station.

2.1.1 Balancing Signal

PNNL developed a stochastic-based methodology for estimating future balancing signals and balancing service requirement as a function of statistical knowledge of forecasting errors in the day-ahead and hour-ahead load and wind production projections [Makarov et al. 2010]. The results of a previously performed analysis that estimate the balancing requirements for the Northwest Power Pool for an increase of wind capacity from about 3.3 GW (2008) to a postulated size of 14.4 GW (2019) were utilized for this study [Kintner-Meyer 2010]. The details of creating the balancing signal for this report can be found in [Kintner-Meyer et al. 2010]. They are roughly outlined as:

1. Determine a future renewable portfolio standard (RPS) scenario and determine the necessary intermittent resource requirements to approximately meet the standards. Select wind resources for meeting the RPS standards.
2. Placement of resources: place hypothetical wind farms at plausible wind sites that have high capacity factors.
3. Scale existing wind and load forecasting errors from the Bonneville Power Administration's (BPA) existing wind sites to new hypothetical wind sites to obtain new balancing requirement components from intermittency of the wind resource. Combine load forecasting error from BPA with that of the NWPP load.
4. Develop a stochastic process that generates a minute-by-minute balancing requirement for the entire NWPP footprint. This assumes a consolidation of all of the existing balancing authorities into one unified balancing area. Furthermore, the output will be the total balancing requirements, derived from total loads and the entire wind capacity.

The above steps required some additional assumption data on the renewable portfolio and load changes in the NWPP. The final results of this analysis suggested additional balancing requirements of about 1.85

GW of incremental and decremental capacity will be required. This would be a total capacity of 3.7 GW (from -1.85 GW to +1.85 GW).

Once generated, the output needed some slight preprocessing to enter a useful format for the renewables integration study. The balancing services of the power output was offset appropriately so no negative balancing services values exist. This operates under the assumption that slower, base generation sources would induce an offset to prevent a negative balancing requirement. Using this offset, the final balancing services output was available. A 10-day sample of the balancing services for August 2019 is shown in Figure 1. The balancing signal for a single day is shown in Figure 2.

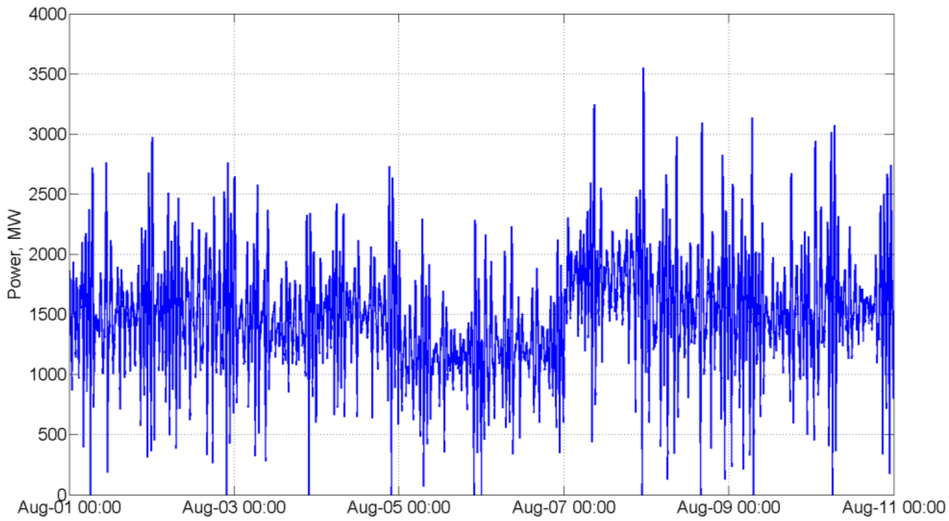

Figure 1. Balancing signal for 14.4 GW of wind generation in NWPP

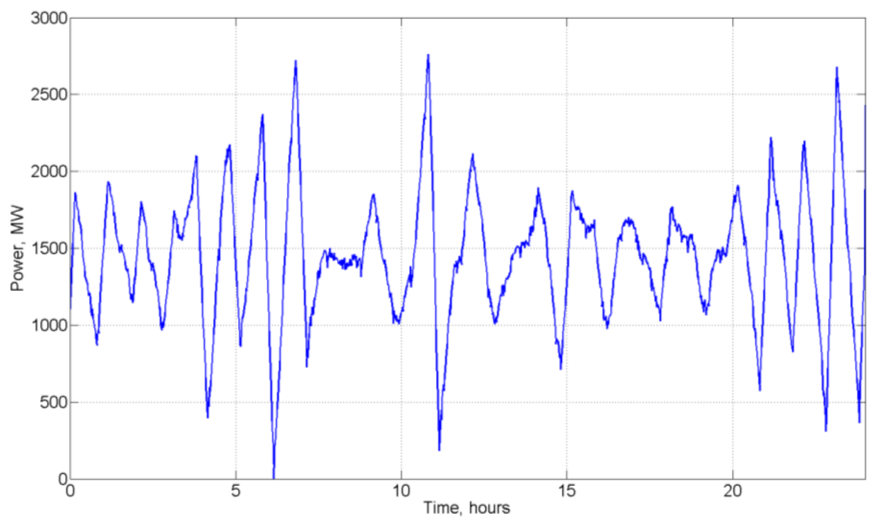

Figure 2. Single day of wind balancing data in NWPP

For the purposes of this study, the frequency of the power grid is used as an indication of overall stress and balancing. The balancing signal from the NWPP simulation is translated into a frequency term using the equation

$$\frac{\Delta P}{D} = \Delta f \quad (1)$$

where ΔP is the change in power, D is a load-damping constant, and Δf is the change in frequency [Kundur 2003; Chassin et al. 2005]. For this study, D was selected to be 94.74 GW/Hz. The selection of this value was obtained by scaling the standard deviation of the frequency value to that of one week of measured U.S. power data. This constant, in conjunction with Equation (1), yields the frequency deviation of Figure 3.

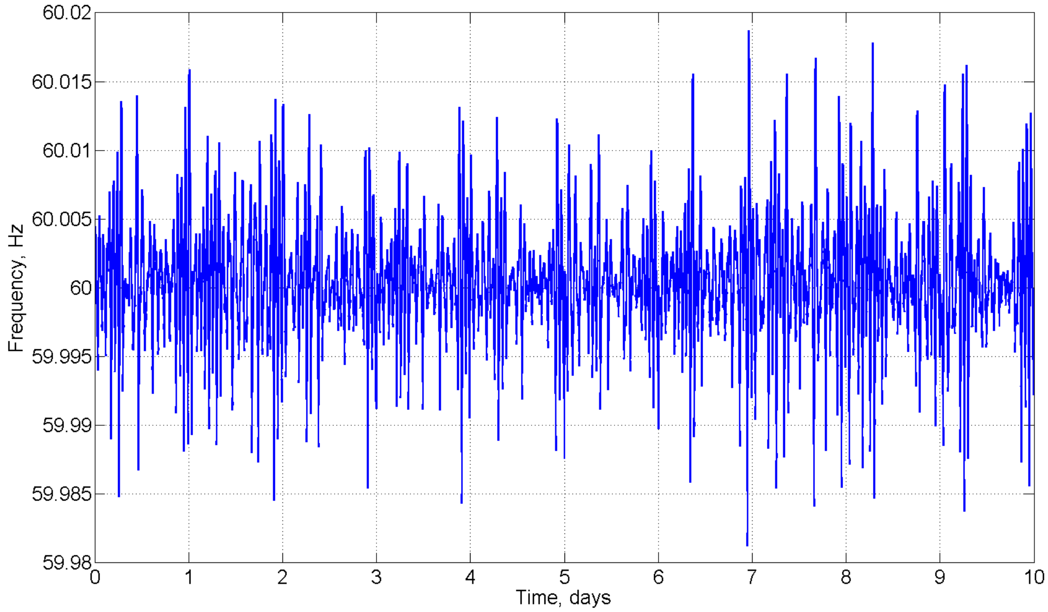

Figure 3. Grid frequency from balancing signal

It is important to note that this frequency value is only associated with the additional balancing from the 14.4 GW of wind generation. This signal is used as the basis for examining if vehicles could meet all of the additional balancing requirements associated with the wind generation. In the real system, the electric vehicles would be complimenting many other balancing methods and generators. Furthermore, the additional balancing requirements associated with the additional wind generation would factor into existing balancing on the system. Therefore, in a real system, not all of the additional balancing requirements would necessarily translate into a frequency deviation.

2.1.2 Vehicle Population and Behavior

To provide a realistic basis that reflects actual driving patterns in the United States, a light-duty vehicle population was built on information from the Department of Transportation's 2001 National Household Travel Survey (NHTS) [U.S. Dept. of Transportation 2003]. The 2001 NHTS data represents a national sample of 26,038 vehicles from a total of 69,817 households. The survey includes many measurements, including trip distance, departure and arrival times, vehicle occupancy, and many others. A small, 1000-sample subset of this data was sufficient for this research to represent driving behavior at sufficient accuracy.

To evaluate the impact of electric vehicles for renewable integration, it is necessary to know the availability of vehicles to be connected to the grid. The duration of availability was determined by querying the NHTS database and extracting the departure and arrival times of vehicles. With time information about the vehicles, it is possible to extrapolate when the vehicle is parked at either home or work, and when it is available for charging and grid services. Furthermore, the departure time provides information about how long the vehicle will be available at a given location, which aids in the charging algorithms. Figure 4 shows the data associated with a small subset of the population of 1000 samples.

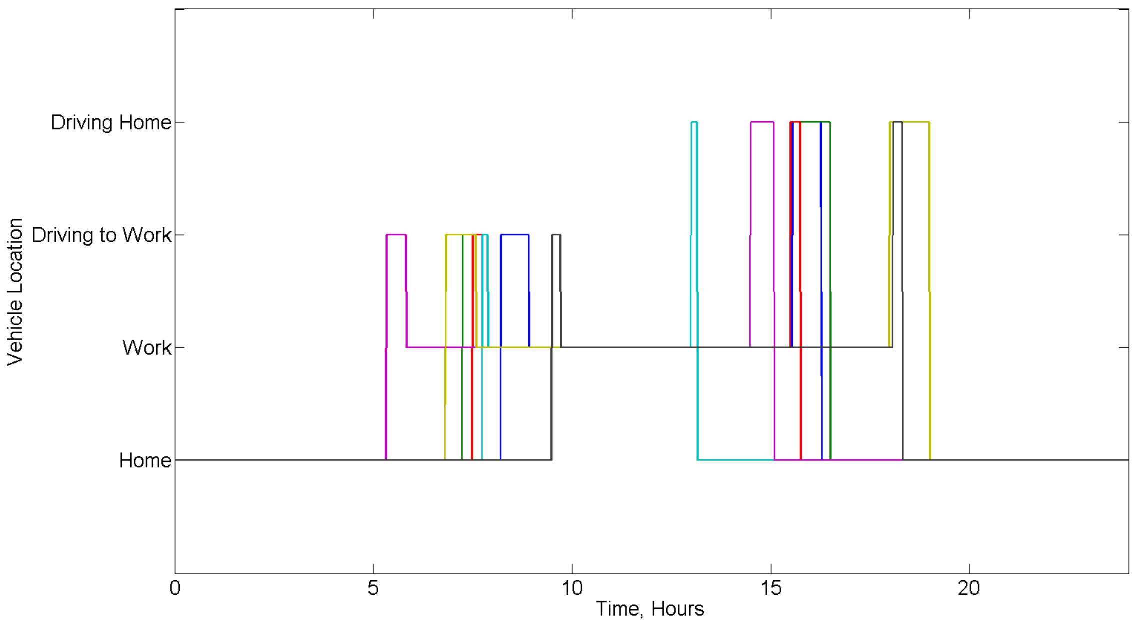

Figure 4. Sample data from 2001 National Household Travel Survey

The other item of interest from the NHTS data set is the distance vehicles traveled. One of the key aspects of this study is to incorporate the energy requirements of the electric vehicles. When a vehicle is stationary, it is able to charge and work towards a 100% state of charge on the batteries. However, for this resource to be available to occur the next day or after a commute to or from work, a discharge must also occur. With the distance information, the amount of energy required to move the vehicle from one location to another can be deducted from the vehicle's state of charge.

2.2 Methodology

2.2.1 Vehicle Assumptions

To explore many different parameters, a simulation framework was established to provide consistency across all of the scenarios investigated. Simulations began with initializing the vehicle population. Once initialized, time-series modeling of the various actions of the electric vehicle occurred.

The framework begins with the initialization of the vehicle population. All parameter investigations in this report utilized a 1000-vehicle population. The total population of 28,038 vehicles was downselected to improve the computation time. It was validated that the downselection did not change the overall statistics of relevant parameters, such as distance traveled or departing and arriving times from and to the home. This population was selected as 1000 random travel profiles from the NHTS data. While the initial selection of vehicles was randomized, all subsequent studies utilized the same 1000-vehicle basis. The underlying properties of the vehicle population remain fixed (unless explicitly modified by a parameter change) for the rest of the simulations. This helps ensure that any changes observed are predominately caused by the parameter adjustments and not a particular sampling of the NHTS vehicle population.

With the 1000-vehicle population obtained, initial properties for each of the vehicles were also assigned. The first parameter of interest was the vehicle type. This was divided into the four categories shown in Table 1. Also listed in Table 1 are the "energy efficiencies" of that vehicular class, as determined from publications of the Electric Power Research Institute's (EPRI) Hybrid Electric Working Group [Duvall 2002, 2004]. This information was necessary as all battery sizes in the study were determined by "optimal range," rather than direct capacity in kWh. That is, all vehicles may be labeled as a 33-mile PHEV (PHEV-33). Obviously, a larger vehicle like an SUV would need a larger battery. However, coupled with the efficiency in Table 1, this larger battery is functionally equivalent in range to a compact car's battery. Variations in the population's battery size are feasible, but were not further investigated in this study to manage the overall scope of the project.

Table 1. Vehicle Types and Efficiencies

Vehicle Type	Energy Efficiency (kWh/mile)
Compact	0.26
Mid-size	0.30
Mid-size SUV	0.38
Full-size/Pickup	0.46

For all scenarios and comparisons in this study, two primary battery sizes were utilized. The first was a PHEV-33-based size. This size represents a plug-in hybrid electric vehicle that is expected to go approximately 33 miles before requiring a recharge, or an alternative energy source (such as an internal combustion engine). The second battery-sized utilized was a PHEV-110 battery size. This is a vehicle that is expected to go 110 miles before a recharge or alternative energy source. The designation PHEV-110 is not necessarily accurate for these scenarios, since the battery size was selected to be similar to upcoming BEVs, such as the Nissan Leaf or BMW Mini-E. Regardless of the terminology, the key differentiating factor to the PHEV-33 was the fact that an electric vehicle with a range of 110 miles required a larger battery, and that based on the driving behavior, more miles could be driven on electricity.

Once a proper battery size was obtained, the vehicle's current state of charge was randomized. As part of this randomization, it is often necessary to remove the first day of simulation results from each parameter investigation. This first day is often used to initialize the population into its charging routine, so some abnormal behavior is often present. Figure 5 shows the first three days of a simulation investigating a particular ratio of home-only and work-home charging. While variations in the individual days are expected (due to the nature of the balancing signal), the first half day is noticeably different.

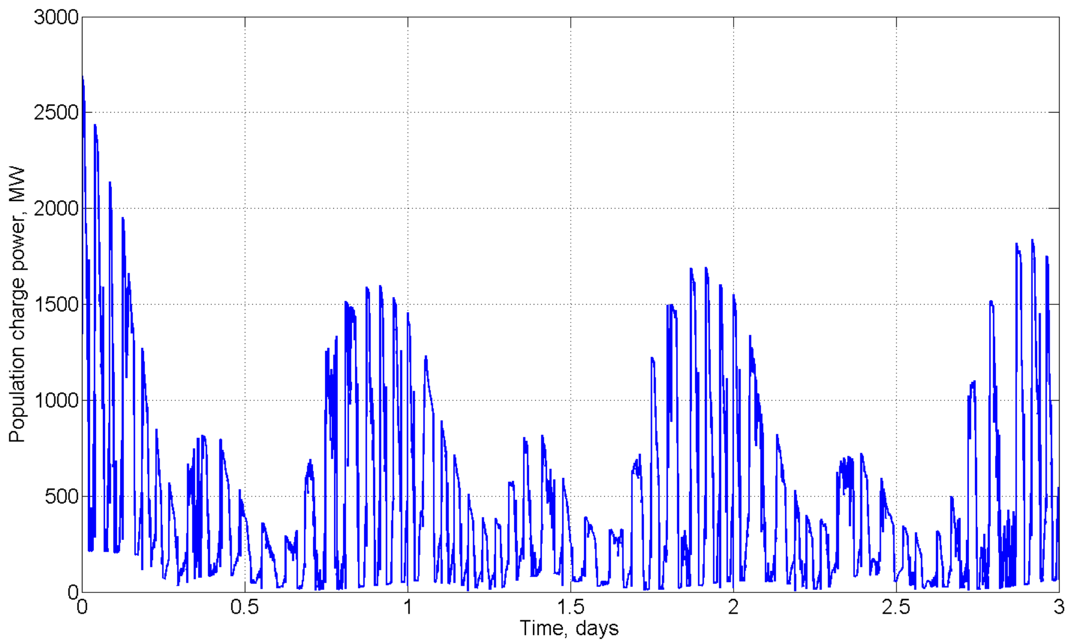

Figure 5. Population charge rate over three-day period

It should also be noted that vehicle battery sizes and states of charge are calculated as the fully available capacity. That is, a 3.0 kWh battery is assumed to have all 3.0 kWh of energy available for use. The industry practice of keeping a battery in an optimal state of charge band (i.e., 25% to 90% [Tate et al. 2008]) to extend life is not utilized here. One can reasonably assume that the battery capacities mentioned could merely be an "adjusted battery size." That is, the 3.0 kWh battery is really a 4.62 kWh battery, but only 3.0 kWh is normally available for use.

Throughout the simulation process, electrical efficiencies were also considered. Table 2 shows the assumed electrical efficiencies for various portions of the model [Kintner-Meyer et al. 2006]. "Battery Charging" and "Battery Discharging" were predominately used in adjustments to the batteries' state of charge during charging and discharging operations. For example, if 1.0 kWh of energy were put into a battery during the charging process, only 0.85 kWh worth of actual capacity would be added to the current state of charge (the other 0.15 kWh is assumed lost to heat, electronic, and chemical processes). "Battery Discharging" operates in an opposite fashion, where the end resulting energy is scaled by the efficiency to determine the discharge amount. For example, a compact car is assumed to require 0.26 kWh to drive a mile. With the battery discharge efficiency, this single mile actually required nearly 0.30 kWh from the battery. "Power Transmission" is not influential on the actual battery state of charge, but serves as an overall scale value for the results shown in Figure 5. That is, if a vehicle population requires 10 kW of instantaneous power, transmission efficiencies mean this actually requires 10.86 kW of power generated.

Table 2. Electrical Efficiencies

Process	Efficiency (%)
Battery Charging	85%
Battery Discharging	87%
Power Transmission from power plant to charging station	92%

With all of the initial conditions defined, the actual time-domain simulation of the charging and discharging cycles could begin. Utilizing the departure and arrival times from the NHTS data, a vehicle's location was constantly checked. If the vehicle was located at home, it was available for charging. If the vehicle was located at work, it would be available for charging only if work charging was available (a parameter of study is the availability of work charging). At each of these locations, the actual maximum charge rate was determined by the availability of 240 Volts, or Level-2, charging at that location. If 240 Volts was available, a maximum charge rate of 3.3 kW was assumed (240 Volts at 13.75 Amps). If 240 Volts was absent, a 120-Volt connection was assumed and a maximum charge rate of 1.7 kW utilized (120 Volts at 14.2 Amps). Other charge scenarios, such as Level-3 DC charging or 240 Volts at 30 Amps were not considered in this study.

If a vehicle was not located at home or work, it was considered in transit. At the beginning of every transit period, the state of charge was immediately adjusted. That is, as soon as a vehicle departed work or home, the necessary energy for the entire trip was deducted from the battery's state of charge. For example, if a compact car had a 10 mile commute, it is assumed to need 2.99 kWh (after efficiency) of capacity to get there. This amount was deducted at the time of departure to reflect the energy requirements for the driving. It is also useful to note here that vehicles are assumed to be PHEVs. That is, if a commute requires more energy than is available in the battery, it is assumed that a combustion engine of some sort allows the commute to finish.

2.2.2 Charging Strategy Definition

The analysis compared the impacts of different charging strategies toward meeting the additional balancing requirements. The charging strategies were defined as follows:

- Vehicle-to-grid-half (V2GHalf) switches the charger into a regulation-based charging mode. Using indications of the grid stress (frequency deviations), the charge current is adjusted. If a rise in frequency occurs, this indicates an excess of generation. As such, a charger employing V2GHalf would increase its charge rate to help offset this balancing. Conversely, if the frequency dropped (indicating a generation shortfall), the charge rate would be reduced. Throughout all of these changes, customer satisfaction is an underlying goal. As such, the algorithm restricts the range of charger variation to try and meet a full battery charge by the imposed deadline (the next commute to or from home). For example, if a vehicle was schedule to go to work in 30 minutes, the V2GHalf algorithm would bias the charge variations such that a full charge condition is met. Figure 6 shows a sample V2GHalf charging scenario. Note the decrease in variability at the 1.8-hour mark as the "charge-by" deadline approaches.

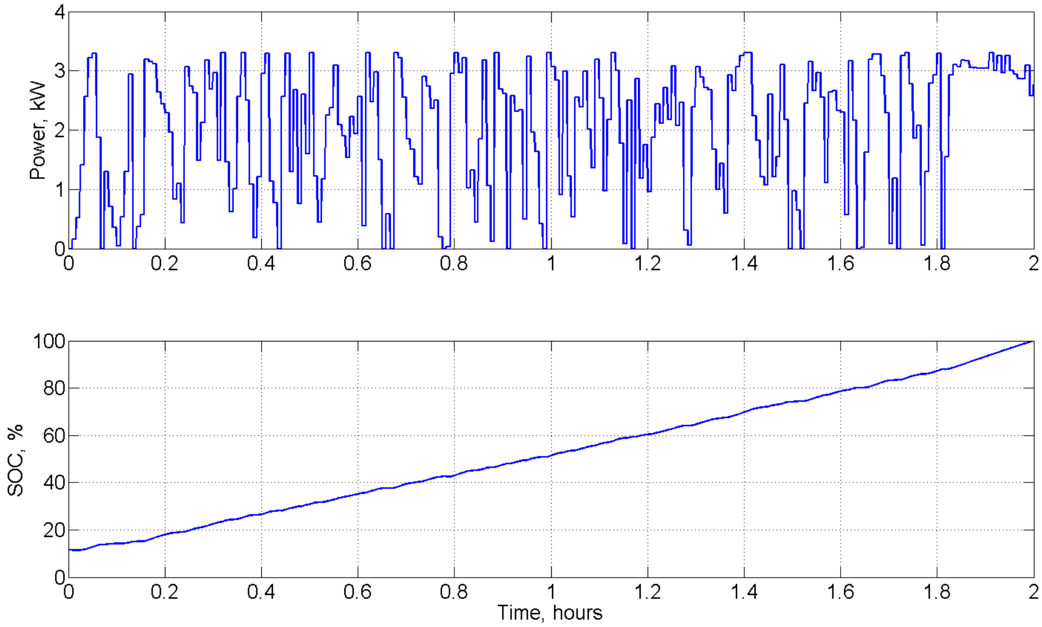

Figure 6. Vehicle-to-grid-half (V2GHalf) charging example

- Vehicle-to-grid-full (V2GFull) charging follows the same methodology as V2GHalf, but also allows a discharge rate on the battery. When stationary, the electric vehicle has the ability to not only take power from the grid, but also provide power back to the grid. Figure 7 shows a sample V2GFull charging scenario. Note again that customer satisfaction is an underlying goal by the decrease in variability and removal of discharging currents around the 2.5-hour mark.

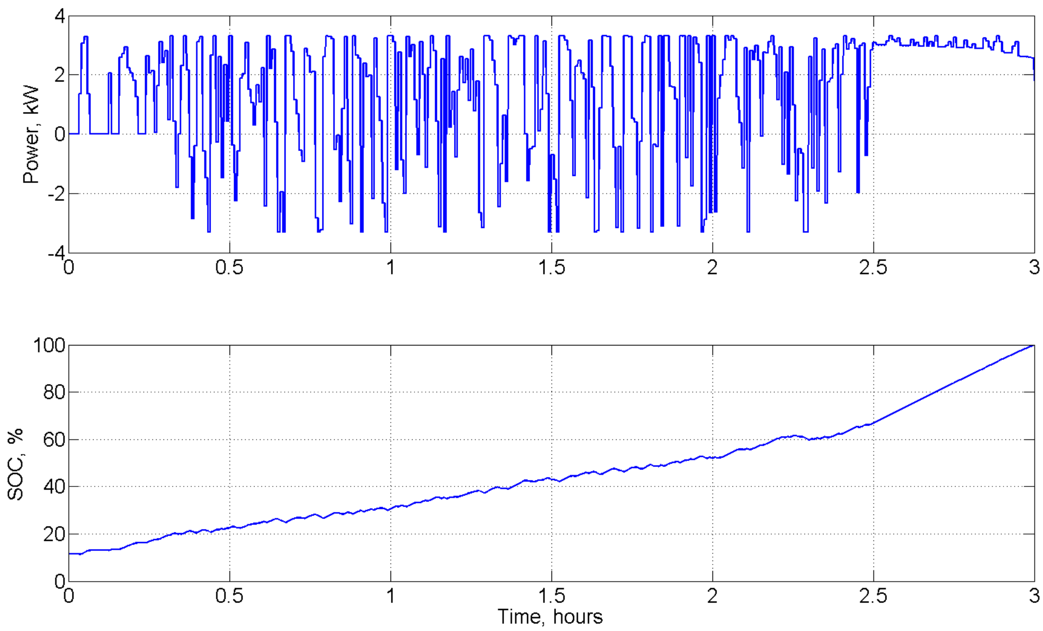

Figure 7. Vehicle-to-grid-full (V2GFull) charging example

Once the individual charge profiles and characteristics of each vehicle were simulated, a population-level charge rate was obtained. This was simply an aggregation of all of the vehicle charge rates for a given time. Figure 5 showed a sample aggregation curve. To determine the number of vehicles required to meet the renewable generation balancing, the current balancing amount was divided by the aggregated charge rate. The result is a time-series of multiples of the current vehicle population needed to meet the balancing requirements. The details of this time-series are presented in the Results section.

Utilizing the base population parameters and the two charging strategies, many different scenarios and parameter sets were explored. It is important to point out that while the results are examined on a population-level, each individual vehicle received a unique, independent simulation. Individual departure and arrival times, battery sizes, charger availability, and state of charge requirements dictated the behavior of each vehicle. Managing each vehicle from an energy-based perspective helps not only improve the viability of the scenarios, but also ensures parameters like battery size are properly considered.

3.0 Discussion of Results

As indicated in the methodology section, each simulation was run on an identical population. The only difference between simulations was related to the parameter of interest. Unless otherwise noted, most parameters were fixed at a 50% value as the parameter of interest varied. For example, if the level of home 240 VAC charging availability was being investigated, other parameters, such as work 240 VAC-charging availability, would be fixed at a value such that 50% of the population has that capability. The major exception to this parameter selection is in regards to work charging availability. Except in scenarios where the work charging ratio is being explicitly investigated, full work charging availability was utilized (all vehicles had the ability to charge at work).

For the parameters explored, often only one population set is examined (e.g., only the PHEV-33 population, or V2GHalf-only scenario). In these cases, the other population scenarios provided similar results and are not explicitly detailed. The simulation figures associated with these results are included in the Appendix.

3.1 Interpreting Plots

Many of the results in this section are presented as a "population versus percent of unserved energy" plot. An example plot is shown in Figure 8. These plots represent the vehicle population required to meet a particular percentage of the balancing requirements. The balancing requirements unserved is expressed in terms of energy not delivered. Such energy is referred to as "unserved balancing energy." It is important to note that the curve of Figure 8 represents the maximum number of vehicles in that population. For the example given, a 10% unserved energy scenario requires 2 million vehicles. Similarly, to meet a nearly 0% unserved energy meaning that nearly all balancing services are met, would require a population of approximately 11 million vehicles. Note that the curve does appear asymptotic near 0%, indicating the vehicle population is never able to meet absolutely all of the unserved balancing energy required.

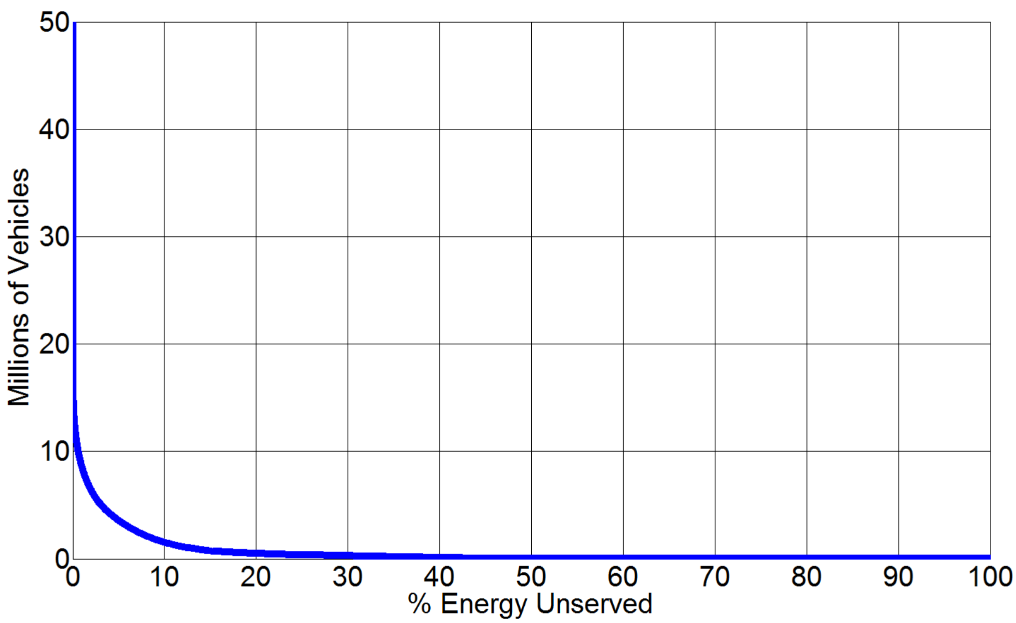

Figure 8. Example population versus percent of unserved energy plot

The values represented in the unserved energy plots are constrained by one further criterion. Any time a negative population multiplier is required, those values are omitted from the current population energy accumulation. These negative population scales coincide to periods where a load reduction was required (excess load compared to generation), but several vehicles were nearing the end of a charging period. Despite wanting to reduce the load on the system, the charging algorithm is trying to meet consumer demand first. Essentially, demand ends up being higher than the wind generation output, representing a load "underserved" condition and requiring additional generation to handle the additional demand.

A simple example would be if the system requires a load reduction at 5:55 pm. However, a particular customer has their PHEV battery at 90% state of charge and wants to leave at 6:00 pm. Despite wanting to ramp down, a full charger output must be maintained to get as close to the user's desired "charge-by" preference. It is important to note that this particular behavior can be dictated by thresholds, or different charging strategies (e.g., if the frequency down deviation is significant enough, grid protection will override customer satisfaction).

The unserved energy plots serve as rough guidelines for how the parameter of interest is affecting the amount of additional balancing not being handled by the PHEV population. Since this only represents a peak population value, it is also useful to examine the impacts of the parameter for a fixed population size. To quantify this relationship, the mean-squared-error (MSE) between the population's aggregate charging curve and the balancing signal is used. Equation (2) provides the basis for the MSE calculation, where $X_{balance}(n)$ represents the additional balancing needed by the wind generation (Figure 5), $X_{population}(n)$ represents the aggregate population charging curve, and N represents the number of discrete samples in the data set. It is important to note that the MSE calculations include the "underserved" load portions of the charging profile, which were omitted in the unserved energy calculations.

$$MSE = \frac{\sum_{n=0}^{N-1} \left(X_{balance}(n) - X_{population}(n) \right)^2}{N} \tag{2}$$

Figure 9 shows a sample MSE curve for a population of 1 million vehicles as a single parameter is varied. For all MSE calculations in this report, an arbitrary population of 1 million vehicles was selected. This number represents only a fraction of the total vehicle population in the United States or the NWPP, but provides a simple basis for examining a parameter's impact on actual grid operations. In this particular case, a parameter value of 0.35 provides the greatest benefit. This result does not necessarily match the unserved energy plots as those deal with maximum allowed populations, while this plot deals with a fixed population size.

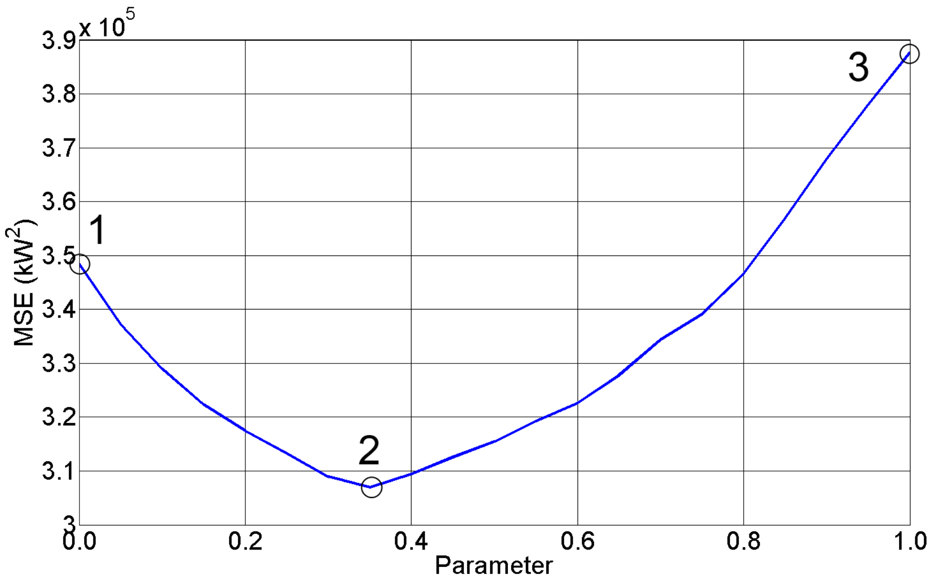

Figure 9. Example MSE plot for 1 million vehicles

Consider Figure 9 further. In this particular MSE plot, a variation of the V2GHalf algorithm was used to examine home-only charging compared to work and home charging. Point 1 in Figure 9 represents the MSE value associated with 1 million PHEVs when none have the ability to charge at work. As a result, the MSE value of the error between the additional imbalance due to wind and the PHEV population response is approximately 3.5 x 10^5 kW^2. As the amount of the population with work charging increases, the value along the *x*-axis increases. Point 2 is eventually reached, which represents 35% of the population having work-charging and home-charging capabilities (roughly 350,000 vehicles). As the plot indicates, this minimum point in the MSE curve results in approximately 3.08 x 10^5 kW^2 for the MSE value between the additional balancing requirements and PHEV response. The trend then increases as the population moves toward point 3, where the whole population has access to both work and home charging. It is important to note that the data of Figure 9 was chosen as a good example for illustrating the MSE curve. This particular charging scenario had some poorly chosen parameters, so it is not reflective of results presented in the later sections.

To provide easily comparable sets of MSE plots, all subsequent plots are scaled the same and provide a normalized MSE. The MSE is normalized against the MSE value associated with none of the additional balancing requirement met. This value represents the MSE of the additional balancing signal itself, with no attempt to meet it with electric vehicles or other resources. The plotted MSE value will represent the percentage of this maximum imbalance data set. Figure 10 shows an example of these “common-scale” MSE plots, with the represented study having less than 0.05% of the error the raw imbalance signal imposes on the system.

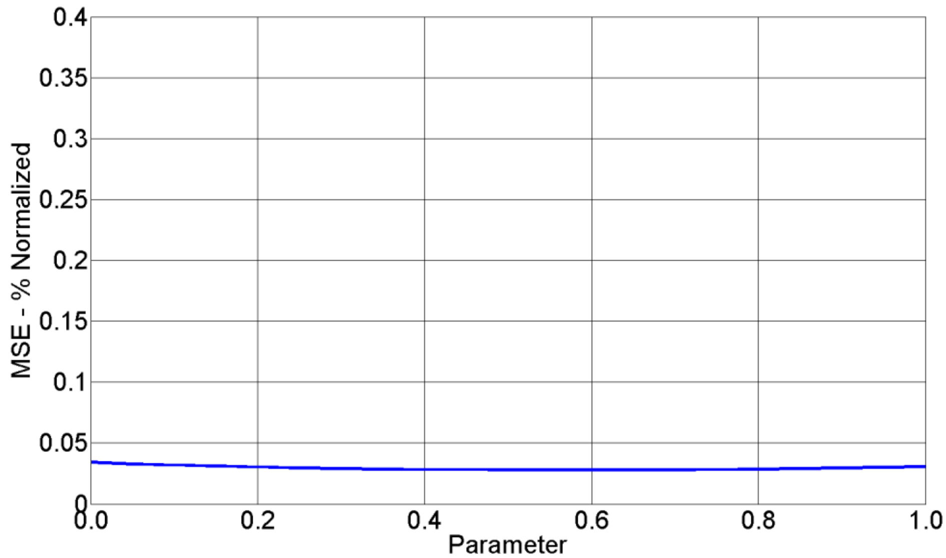

Figure 10. Example common-scale MSE plot for 1 million vehicles

Coordination of the results of Figure 8 and Figure 9 is often necessary. Figure 8 shows how the altered parameter influences the maximum population size required to meet the additional balancing requirements. The MSE plots in the style of Figure 9 demonstrate how the parameter being adjusted matches against the actual balancing requirements. Figure 8 shows the theoretical balancing requirement a certain population could reach, while Figure 9 and Figure 10 show the influence on a static population size. The combination of the two plots helps provide a means for evaluating the simulation results for a variety of different property investigations on the population.

3.2 Vehicle-to-Grid-Full (V2GFull) – Full Resource Availability

To explore the limiting case, a scenario is defined in which the vehicle is assumed to be plugged in for 24 hours performing V2GFull services. This is the functional equivalence of a stationary energy storage system. This case provides a lower bound on the number of vehicles required to meet all of the balancing requirements against which other scenarios can be compared.

In this scenario, a large vehicle battery of 100.0 kWh is available. This battery is arbitrarily sized to ensure the balancing services remain unconstrained, i.e., never constrained by either full conditions or empty conditions. The size is also chosen to allow the particular algorithm for V2GFull to function in a manner similar to the rest of the report. Since the vehicle is assumed to have full availability, no "travel discharging" ever occurs to drain the battery significantly. This requires a larger battery size than realistically needed, since a fixed energy storage device would also discharge into the grid at a constant rate to reduce its state of charge.

A baseline simulation is run and then appropriately scaled to meet the balancing signal. The resulting unserved energy plot is shown in Figure 11. The unserved energy approaches nearly zero at a population size of roughly 560,000 vehicles. This means that a population of about 560,000 vehicles, operated as distributed stationary energy storage systems, will provide all of the balancing requirements.

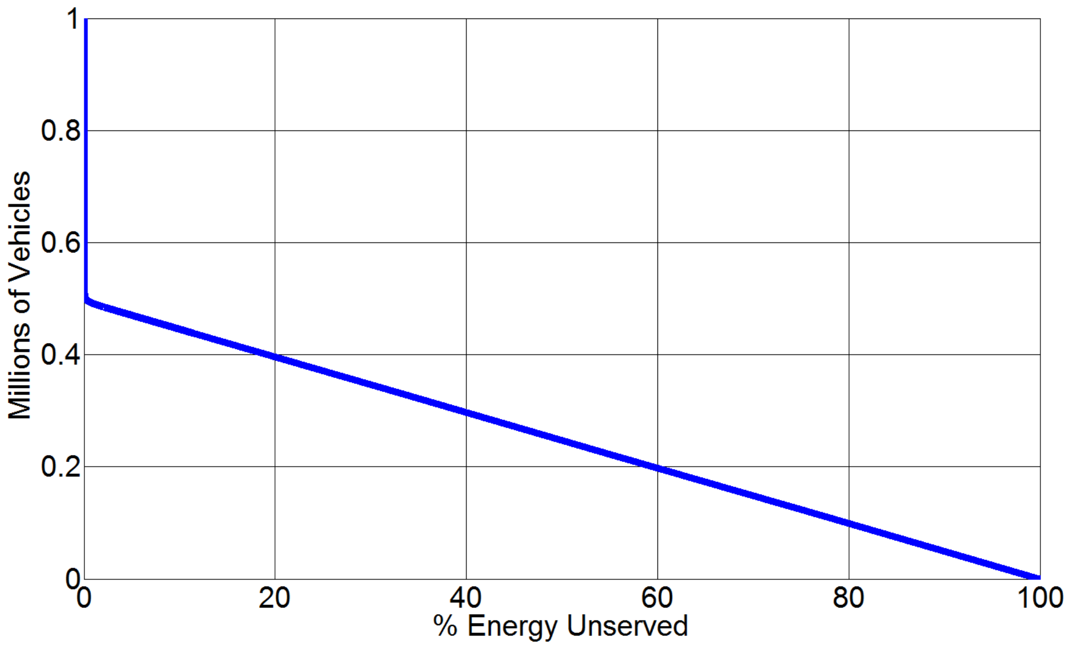

Figure 11. Percent of Unserved energy for ideal V2GFull Implementation

Further investigation of the results revealed that the full 100 kWh battery was not needed. Over the simulation interval, a minimum battery capacity of 2.5 kWh was required. If this required battery size were replicated to the full 560,000-vehicle population, this would mean a battery size of approximately 1.2 GWh would be required.

It is important to point out that the primary constraints for Figure 11 are the rate of charge and discharge for the battery, and the storage size available. If the charging and discharging rate were increased, fewer vehicles would be needed. However, a larger storage capacity would be required to retain availability for the full period. If a smaller battery capacity is utilized, a slower charging and discharging rate would be required, along with a proportionally larger population.

Roughly 560,000 EVs/PHEVs with 2.5 kWh of storage performing V2GFull over a 24-hour period would be needed to meet the additional balancing requirements imposed by the addition of 10 GW of wind to the NWPP. With limited availability, however, more vehicles are required to meet the additional balancing requirements.

3.3 V2GFull – Availability Constrained by Driving Patterns

The previous section explored a limiting case based around the concept of a stationary energy storage device represented by a population of vehicles with full availability. To provide a more real-world scenario, vehicles were analyzed with 2001 Department of Transportation driving patterns.

Figure 12 shows the results for such a scenario. The population simulated assumes full work-charging availability, so the resource is physically available for any part of the day it is not commuting. Figure 12 contains information for populations of both PHEV-33 and PHEV-110 electric vehicles. As indicated in Figure 12, the difference between the PHEV-33 and PHEV-110 populations is very minor. Unlike the ideal, full availability conditions of the previous example, these vehicles are subject to normal use constraints from the NHTS data. This includes commute times, as well as the underlying need for a vehicle to be fully charged by certain times of the day (e.g., before leaving for work). The charge level constraints and brief interruptions in availability are enough to require approximately 2-3 times the size of the population of the stationary storage scenario.

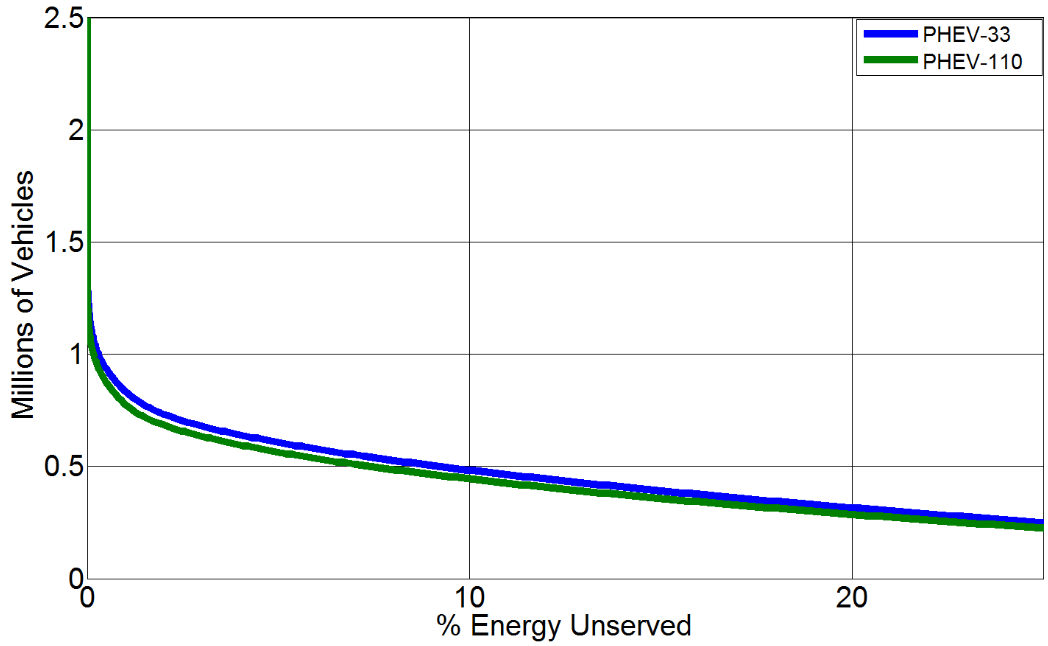

Figure 12. Unserved energy percentage for ideal V2GFull charging scenarios

The populations in Figure 12 also highlight an important result. The PHEV-110 population, with a larger battery, is able to handle more of the energy. While not a significant difference, this additional capacity results in greater availability. As a result, fewer vehicles are needed to meet the same unserved energy requirements than in the PHEV-33 scenarios. However, the differences between a small battery for a PHEV33 and a large battery PHEV110 are relatively insignificant. Despite the increased "availability" of the larger PHEV-110 battery, the underlying charge rate limitations (level 1 or level 2) are the same for both vehicle types. If the charge rate limitation were proportional to battery size, or higher current level 2 or DC charging were utilized, the difference between the required PHEV-33 and PHEV-110 populations is expected to be greater.

3.4 Balancing Services Charging – V2GHalf Compared to V2GFull

Compared are the impacts of charging strategies on the numbers of vehicles required to meet the balancing requirements. In the algorithm utilized for these studies, the V2GHalf charging operations cease when a 100% state-of-charge is reached. However, V2GFull's ability to discharge into the grid allows it to remain an active regulation device for longer and may provide additional benefits.

Figure 13 shows the results for varying population levels of V2GFull. At the 0% parameter point, the entire population is using V2GHalf as the charging algorithm. As the percentage increases, more vehicles of the population are using the V2GFull charging scheme. As Figure 13 shows, a lower V2GFull population level requires a noticeably higher population to meet the additional balancing requirements of the wind generation. As the V2GFull population ratio increases, this total number of vehicles eventually becomes about half that of the V2GHalf-only charging population. The ability for the V2GFull charging strategy to discharge back into the grid, and maintain resource availability for a longer period of time, appears to enable a much smaller vehicle population to handle the additional balancing requirements.

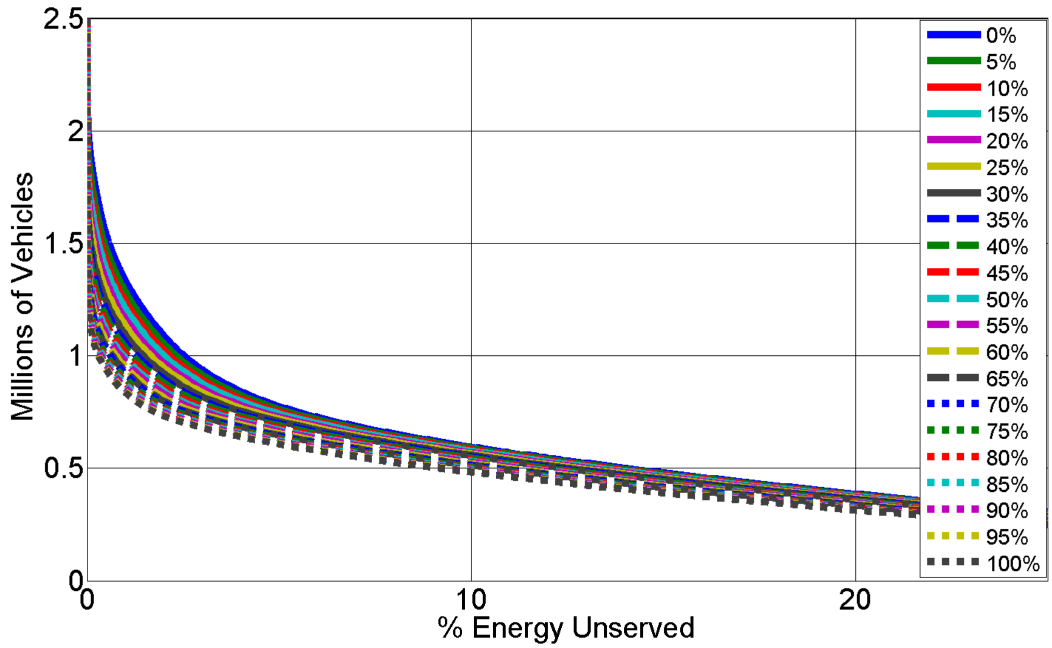

Figure 13. Unserved energy percentage for V2GHalf vs. V2GFull charging scenarios - PHEV-110 (note 0% means all vehicle perform V2Ghalf; 100% means all vehicle perform V2Gfull)

The MSE values in Figure 14 for the evaluation show slightly different results. As the V2GFull portion of the population increases, the mean-square-error increases. In this aspect, the two plots in this subsection show conflicting information. The unserved energy plot shows that an increase in V2GFull-based charging results in significantly less unserved energy. However, the MSE associated with this population increases. The increase is not significant, especially when considering a PHEV population using only the V2GFull strategy required roughly half as many vehicles to meet the additional imbalance. However, it does indicate that the increase of V2GFull on the population results in slightly more "errors" in tracking the additional balancing requirements.

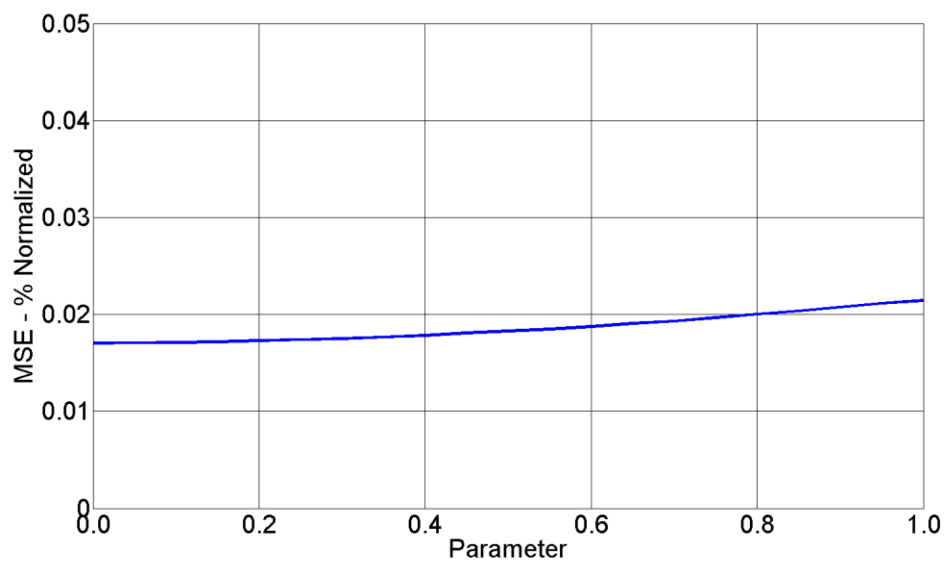

Figure 14. MSE for V2GHalf vs. V2GFull charging scenarios - PHEV-110

Further examination of the simulation results reveals the source of the increase in MSE. As a higher percentage of V2GFull is deployed, more of the regulation down energy can be met. At the same time, these vehicles are still trying to reach a desired state of charge. This overall "customer criterion" drives the charging aspect slightly higher than the V2GHalf populations. What results is a slight "over-compensation" of the additional balancing requirements, which results in a slight offset in the power output. This slight offset influences the MSE as a persistent, larger error term. It is important to note that this scenario only attempts to utilize electric vehicles to provide the additional balancing requirements. With such a persistent term in the MSE value, other resources in the energy market could compliment the vehicle population and reduce this persistent MSE term.

3.5 Balancing Services Charging – Home Level 2 Charging Availability

Another parameter of interest in using PHEVs to offset the additional balancing created by 10 GW of additional wind capacity in the NWPP is how level 2 charging at home will influence the results. Recall that level 2 charging is a faster charging rate associated with a 240-Volt AC interface instead of the standard 120-Volt AC interface. With a higher voltage (and higher current value), the PHEV can charge (and discharge, if V2GFull-equipped) at a higher rate. The impact of this improved charging rate is explored here.

Figure 15 shows the resulting percentage of unserved energy plot for varying availability of 240-Volt charging when the vehicle is at home. Despite the increased charging rates associated with the level-2 installations, the availability of Home 240-Volt charging has little influence on the unserved energy percentages. Even with 100% of the population having 240-Volt charging available, there is no significant impact to the unserved energy on the system.

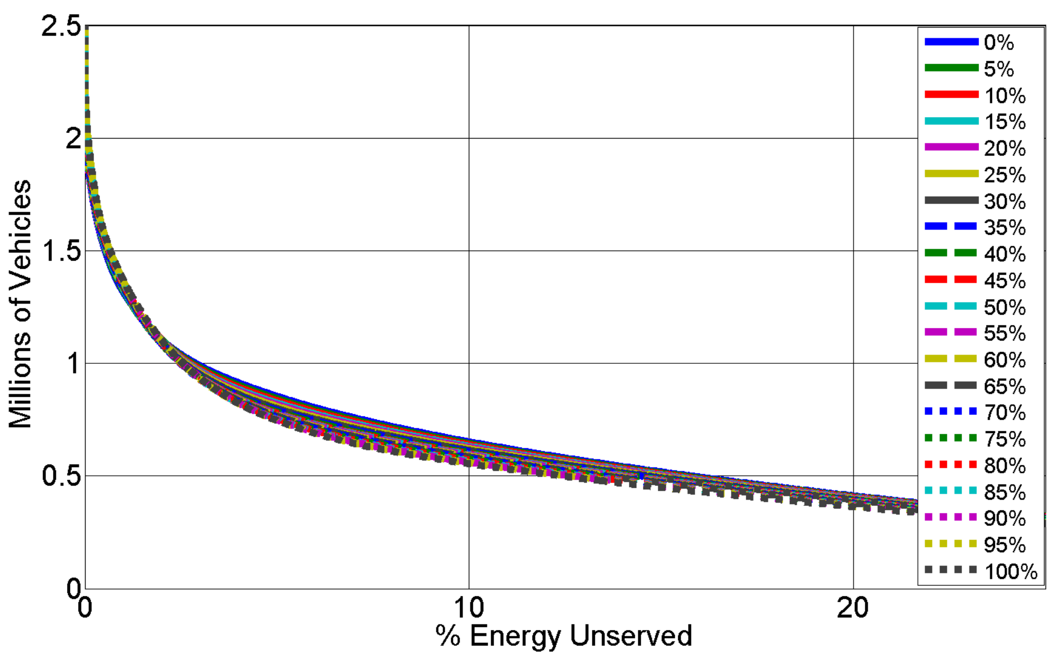

Figure 15. Unserved energy percentage for home Level 2 charging availability - V2GHalf only - PHEV-33 (note 0% means all vehicle charge at Level 1; 100% means all vehicle charge at Level 2)

A plot of the MSE values for increasing levels of home 240-Volt charging is shown in Figure 16. The MSE values increase slightly as the home level-2 charging population increases. However, it is important to note that the overall increase in "error" on the system is not that significant between a population of only level-1 home charging available (0%) and all level-2 home charging (100%). Despite the higher charging rate, the ability to charge using 240-Volt appears to be a slight detriment to the grid, rather than a benefit.

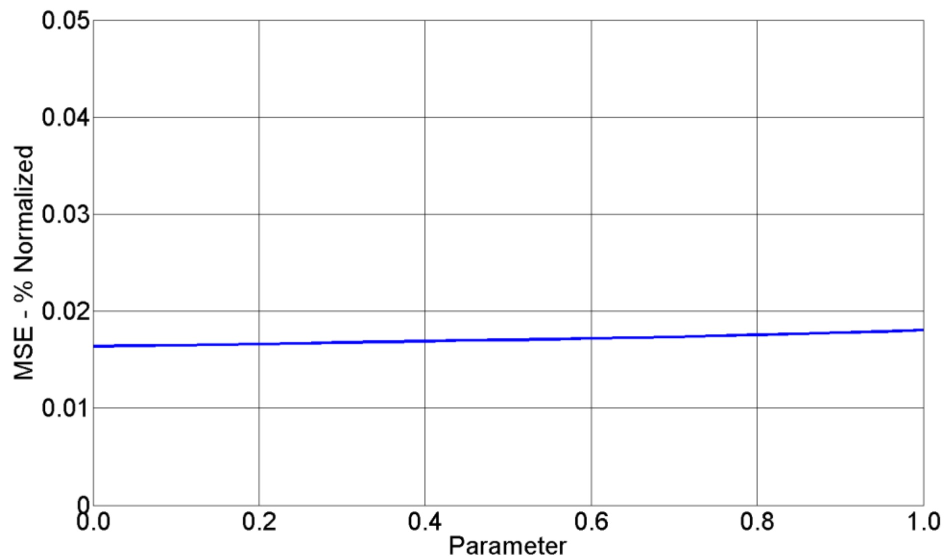

Figure 16. MSE for home 240-Volt charging availability - V2GHalf only - PHEV-33

While counterintuitive at first, the results for home 240-Volt charging availability do make sense in terms of the overall system. Most of the simulated population has a typical "workday" schedule where the vehicle is parked at home from approximately 6 pm until 6 am the next morning. With 240-Volt charging available, the battery will be charged that much more quickly. As a result, the resource becomes unavailable earlier in the charging period. When needed to meet the additional balancing requirements in the early morning hours, many of the vehicles have already met their charging requirements and are unavailable. The result is a larger amount of unhandled energy, as well as an increase in the MSE value.

3.6 Work Charging Availability

While the availability of home-based level-2 charging was an important parameter to investigate, the final population parameter investigated has the potential for much larger impacts. The ability to charge a PHEV while at work could be a service to the grid, or it could exacerbate problems with peak demand during critical times. This section explores the potential benefits, or detriments, a PHEV population would impose on power grid under varying availability-levels of work charging.

3.6.1 V2GHalf Only - PHEV-110

With the ability to charge at work available, EVs/PHEVs can be providing balancing or regulation services during the day while parked during working hours. Here, the impacts of an increasingly available work-charging infrastructure are explored.

Figure 17 shows the results for different levels of work-charging-availability, but with a population that only utilizes V2GHalf regulation-based charging. The results indicate that a relatively small change in the work-charging availability (5% work charging availability) causes a significant reduction in the population to meet a particular unbalanced energy requirement. As the availability of work charging increases in the V2GHalf scenario, the unserved energy value continues to decrease, further offsetting the additional balancing requirements of the additional 10 GW of wind generation.

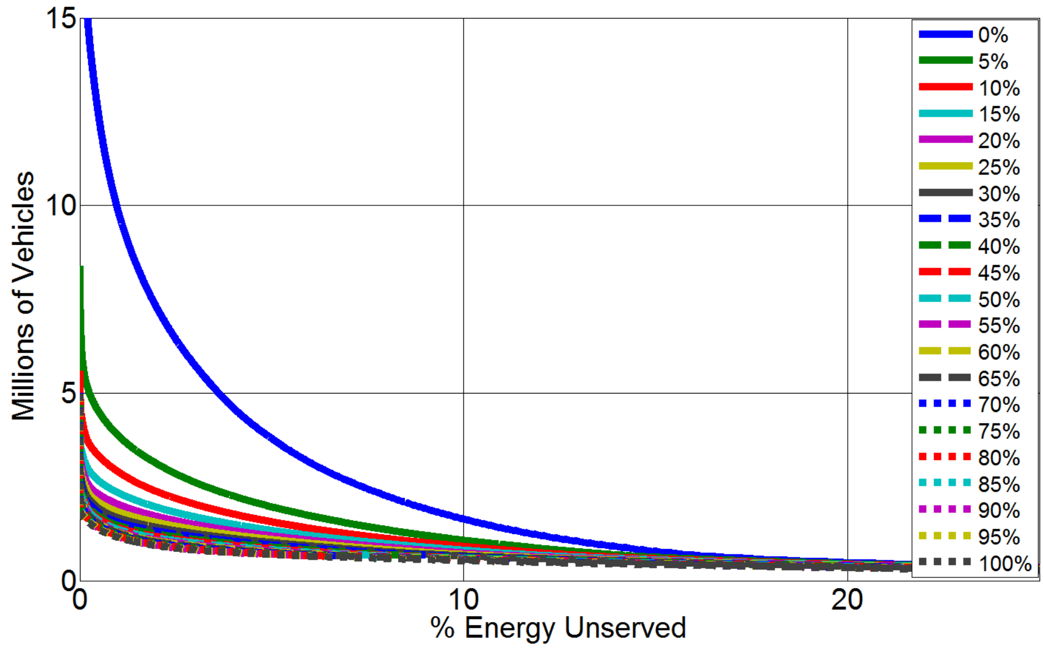

Figure 17. Unserved energy percentage for work charging availability, V2GHalf only - PHEV-110

An alternative representation of Figure 17 is to plot the required population to handle all of the energy for the different work charging availability values. Figure 18 shows a plot with this information with the varying availability level on the *x*-axis and the population required on the *y*-axis. Figure 18 takes the left-most edge of Figure 17 and plots it along the parameter axis. As Figure 18 demonstrates, the population required to meet the additional imbalance associated with the additional wind generation decreases as the work charging availability increases. As with the unserved energy plot, the most significant reduction occurs between the 0% and 10% availability scenarios. Subsequent gains are not as significant, implying that even having a population where 10% of the vehicles are allowed to charge at both home and work will provide 80% of the benefit to the power grid.

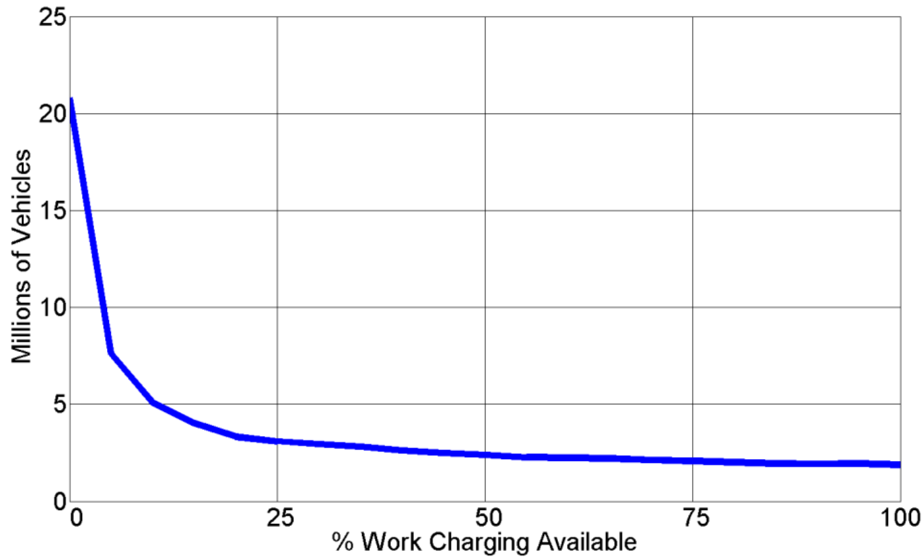

Figure 18. Population required to meet full additional imbalance - V2GHalf only - PHEV-110

The V2GHalf charging scheme also shows a benefit to the MSE as the work charging availability is increased. Figure 19 demonstrates that there is an optimal point. Once over 65% of the V2GHalf-based population is able to charge at the work place, the mean-squared-error begins to increase again. This is indicative that the PHEV population charging at work is no longer meeting the balancing, but is actually exceeding it. However, the absolute errors are still relatively small across the entire parameter space.

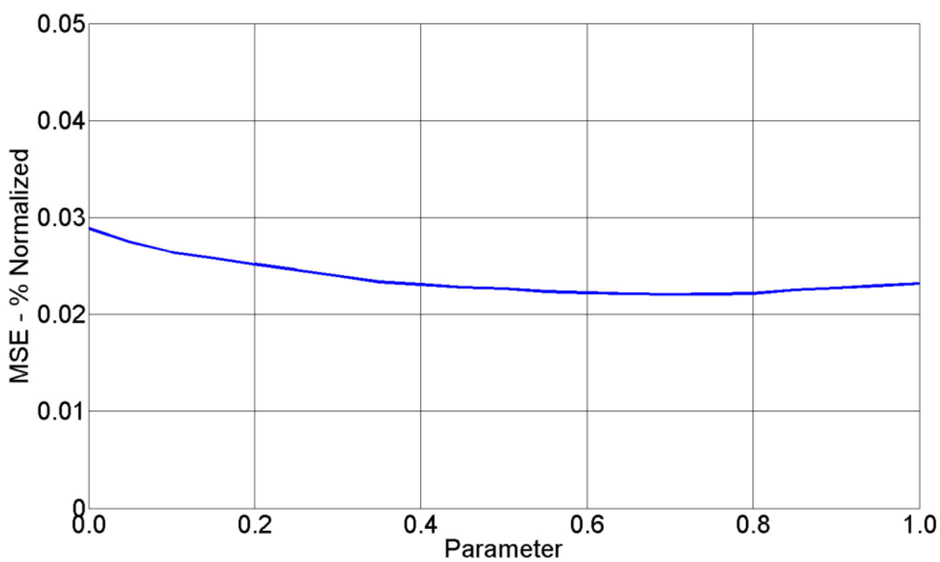

Figure 19. MSE for work charging availability - V2GHalf only - PHEV-110

3.6.2 V2GHalf and V2GFull - PHEV-110

Next, the influence of work charging availability given a population of vehicles with 50% V2GFull and 50% V2Ghalf capabilities is explored. The ability for half of the work-charging population to discharge into the grid and provide additional availability may provide even further benefit to the grid.

Figure 20 shows the results for different levels of work charging availability. Similar to the V2GHalf versus V2GFull subsection earlier in this report, the V2GFull algorithm results in a smaller population requirement to meet the additional balancing requirements from the wind generation. Furthermore, just as was the case in the V2GHalf-only charging, the introduction of work charging provides a significant reduction in the number of PHEVs needed to reach a particular unserved energy percentage. Even a very small work-charging allowance, such as 5%, provides a significant shift in the unserved energy curve.

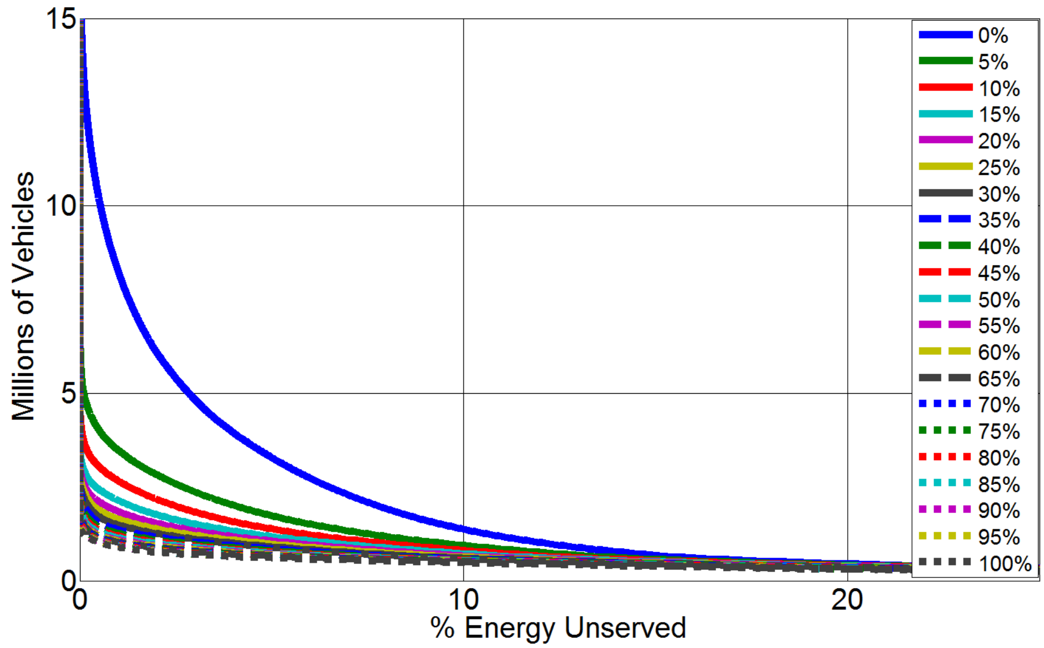

Figure 20. Percentage of Unserved energy for work charging availability - V2GHalf and V2GFull - PHEV-110

Just like the previous subsection, it is useful to examine the population requirements to meet all of the additional balancing requirements associated with the introduction of the 10 GW of additional wind generation. Figure 21 shows the plot of the population required at each level of work-charging availability. Similar to the V2GHalf charging results presented earlier, the largest change in the population occurs between 0% and 5% of work charging availability. Again similar to the V2GHalf and V2GFull plot earlier in the report, the introduction of V2GFull-charging reduces the population required by about 2 million vehicles over V2GHalf-only charging.

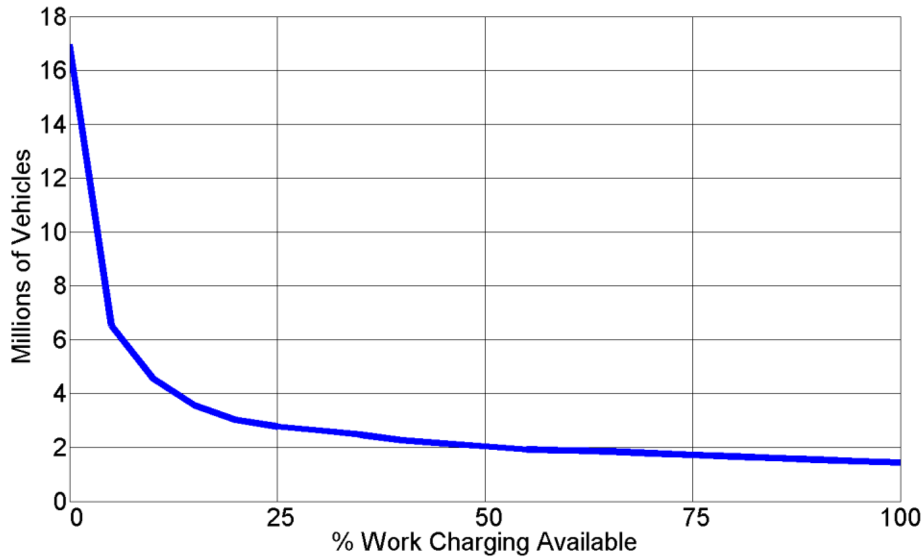

Figure 21. Population required to meet full additional imbalance; V2GHalf and V2GFull - PHEV-110

Figure 22 shows additional benefits of the V2GFull portion of the population. While a similar shape to the V2GHalf-only population of Figure 19, the minimum MSE value occurs at a lower work-charging-availability percentage. At 60%, the V2GHalf and V2GFull population exhibits an optimal balancing handling point. The introduction of V2GFull capabilities in the population allows a larger portion of the additional imbalance to be met. Although the MSE values are slightly higher than those for the V2GHalf-only scenario presented, the additional unserved energy handled (reduced down to around 4% or 5%) provides significant benefit to the grid.

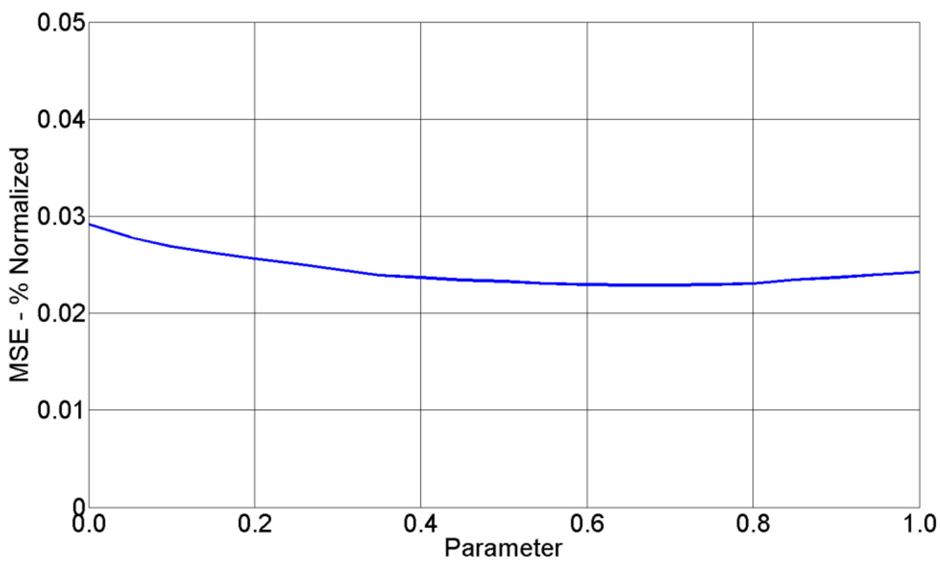

Figure 22. MSE for work charging availability; V2GHalf and V2GFull - PHEV-110

4.0 Observations and Conclusions

After completing a set of analytical simulations that explored the sensitivity of various parameters on the total number of electric drive vehicles necessary to meet the balancing, the following insights were gained:

1. The estimate of about 3700 MW of additional balancing requirements to support a 14.4 GW wind supply in the NWPP could theoretically be supplied by electric vehicles, provided that the population of electric vehicles are charged in a controlled fashion, either employing a modulated charging (V2GHalf) or a modulated charging/discharging strategy (V2GFull). In either case, when compared to the existing stock of light-duty vehicles (cars, SUVs, pickup trucks and vans) in the NWPP footprint (WA, ID, OR, UT and parts of MT), the required number of vehicles would range between about 8% and 180% of the existing light-duty fleet. The percentage values are based on 2001 motor vehicle registrations data in WA, OR, ID, UT, and MT of about 16.5 million vehicles [DOT 2002].

   The high percentages of the vehicle stock requirements (that is over 100%) correspond to the scenario in which the vehicles would only be charged at home and thus, only very few vehicles that are parked at home during the day would contribute toward meeting the balancing requirements (see Table 3 below). The lower numbers of the percentage range reflect the larger resource availability of electric vehicles by being able to charge throughout the day (primarily at work). The mid-range reflects assumptions of a portfolio of vehicles, some of them being able to charge at home <u>and</u> at work, while the others only charge at home. A limiting case was defined that postulated that all vehicles be available 24 hours per day – 7 days a week performing V2GFull services. This limiting case is identical to a distributed stationary energy storage system dedicated to perform balancing services. For this limiting case, a total number of about 560,000 vehicles (4% of light-duty vehicle stock) would be necessary with a Level 2 (3.3 kW) charging/discharging technology. The necessary electric energy capacity in each vehicle could be relatively small (about 2.5 kWh) since not much energy is being moved in and out of the battery.

   Overall, this study revealed a significant potential of the emerging electric vehicle fleet toward meeting some of the growing balancing services that grid operator will need to harness the fluctuations in the production of wind and solar energy technologies. While a V2GFull operating mode may have some market acceptance barriers to overcome, V2Ghalf would not be encumbered with these issues. V2Ghalf strategies only require a modulation of the charging current without violating the users' desire to have the battery fully charged at a certain time. If about 13% of the existing light-duty vehicle stock (about 2.1 million vehicles) were PHEVs with a 33-mile electric range and applied V2GHalf charging strategies at home and work, all of the additional balancing requirements of 3.7 GW could be provided by the electric vehicles. The next paragraphs discuss sensitivities of the key parameters of the analysis on the overall results.

2. A comparison between V2GFull and V2GHalf confirmed that the individual larger capacity that V2Gfull service offers to the grid (6.6kW=3.3kW – (-3.3kW)), which is theoretically double the capacity of V2Ghalf (3.3kW), requires a smaller number of vehicles to meet the additional balancing constraints. As shown in Table 3, the V2Gfull service requires on average about 30 to 35% less vehicle than does the V2Ghalf approach across all scenarios. The fact that the V2Gfull charging strategy is limited in using the entire charging and discharging range (+3.3 kW to -3.3 kW) in the very beginning and toward end of a charging cycle is the reason why the reduction in vehicles required is only 30 to 35% less than that for V2Ghalf, and not 50% less. When the vehicle arrives at a charging station with an almost empty battery, despite the fact that V2Gfull exist, the battery management system will not allow to further discharge the battery for providing balancing services.

Similarly, the V2Gfull is limited toward the end of the charging period when only balancing services in the discharging mode are permitted.

3. The results are relatively insensitive to the charging level. A comparison between Level 1 and Level 2 charging revealed very little differences (see Figure 15). This suggest that the apparent advantage of higher electricity demand of Level 2 charging (3.3 kW) compared to Level 1 charging (1.7 kW), does not reduce the number of vehicles to meet the balancing requirements in the proportion of the charging limits. A detailed study of the actual operation of the different charging populations indicates that the faster charging vehicles require less time to charge, which in turn requires more vehicles to meet the balancing requirements over a given period. The slower charging vehicles provide less capacity than do the faster charging vehicles, however, the individual charging periods are longer. This means that a population with less resource capacity, but longer charging periods, is functional equivalent to resources of a higher capacity, but shorter charging periods. This insight is important because it contradicts the conventional assumptions that capacity (i.e., electricity demand) is the sole criterion for characterizing the resource. While this understanding holds true for generators that are not energy-limited. It is not valid for battery charging in vehicles that have an energy limiting constraint. The resource of a vehicle providing balancing services vanishes once the battery is fully charged.

4. The results indicate a strong relationship of the charging station availability throughout the day (referred to as "charging at work") on the total number of vehicles required to meet the balancing requirements. The results, furthermore, reveal a behavior of diminishing returns after the vehicle stock is offered a certain amount of charging stations at work. As was shown in Figure 18 and Figure 21, 80% of the improvements by offering public charging stations at work can be achieved with about 10% of public stations. This has significant policy implications, which will be discussed below.

5. The question of whether or not the size of the vehicle battery matters for supplying balancing services, can be answer with results shown Table 3. For the *home only* charging option, the larger battery (PHEV 110) reduces the number of required vehicles in the range of 17% to 30%, while for *home and work* charging options, the improvement potential is only between 7% and 10%. These results are plausible. It suggests that when charging at work is available that the commute to work will deplete the battery in terms of kWh in both vehicles types (PHEV33 and PHEV110) to about equal amounts freeing up resources for re-charging to a similar amount. When charging at work is not available, then the PHEV33 will, in several cases, run on gasoline because of the smaller battery. Under this condition, the PHEV110 will offer a longer re-charging period, thus, offering the resource for a longer period of time, which overall reduces the number of required vehicles.

   Also shown in Table 3 and highlighted earlier in Figure 12, the population difference between the two vehicle scenarios (PHEV33 and PHEV110) are not as significant as expected. The overall charge and discharge rates are the same for both PHEV33 and PHEV110, so even in situations of adequate vehicles, the rate at which at PHEV33 or PHEV110 can provide the service is the same. If the charge rate were a higher form of Level 2 (30 Amp charging limit) or high-Voltage DC charging, this difference may be more significant.

Table 3. Population of Vehicles Required to Meet Additional Balancing Requirements (percentages are based on 16.5 million light-duty vehicles in NWPP)

Charging type	Battery Size Scenario				
	Stationary Storage	PHEV 33		PHEV 110	
		Home only	Home and Work	Home only	Home and Work
V2GHalf	-	29.7 mill (180%)	2.1 mill (13%)	20.8 mill (126%)	1.9 mill (12%)
V2GHalf and V2GFull	-	21.8 mill (132%)	1.6 mill (10%)	17 mill (103%)	1.4 mill (8%)
V2GFull	0.6 mill. (4%)	18.6 mill (113%)	1.4 mill (8%)	15.5 mill (94%)	1.3 mill (8%)

5.0 Significance and Implications of Results for Renewable Energy Technology Integration

The results indicate that the emerging electric vehicle fleet could make a substantial contribution toward meeting the new balancing requirements associated with the grid integration of growing wind technology deployment. To what degree this potential can be realized in the future will depend on the economics of the implementation and a viable and compelling business model either for the individual electric vehicle owner, or a third-party service provider. Other demand response technologies, particularly residential electric hot water heaters and large industrial customers, are likely to compete for the same market share. While several million hot water heaters are already installed in residential and commercial buildings, electric vehicles still have to prove their market acceptance. However, the international automotive industry has made significant investments in battery and electric vehicle technology, giving rise to the anticipation that electric vehicles will play a role as transportation means. With an optimistic outlook of future market adoption of PHEVs and EVs in the U.S., 10% of the light-duty vehicle stock could be achieved by about 2030 [Balducci 2008].

The proposed frequency-based charging strategy, either in its implementation as V2GFull or V2GHalf, has some very significant cost advantages to traditional command and control strategies that require communication means to control generators and load participants second by second. By utilizing the frequency deviations as a control variable to minimize the Area Control Error (ACE), no communications means is necessary. The local AC grid frequency is a necessary signal for the grid operators to balance load and generation to maintain the nominal grid frequency. While frequency products are part of the market design of ancillary services in the UK, they do not currently exist in organized wholesale market in the United States [Heffner 2007]. The challenge that such a frequency-based distributed control strategy would face is to be adequately rewarded for the service it provides. To-date, V2GFull pilot studies are performed with full communication equipment as required for large generators. While communications is always a technical option, for relatively small resources, such as an electric vehicle charger (up to level 2), the economics of both V2GFull and V2GHalf are doubtful.

The analysis explored the incremental improvement of V2GFull over that of V2GHalf and found that improvement potential, in terms of less vehicles necessary for meeting the balancing requirements, are in the range of 30% to 35%. While this range is a significant improvement, the fact that currently all EV and PHEV manufacturers do not allow discharging the transportation battery into the grid without voiding the battery warranty may pose a significant barrier to this strategy, at least for the near-term. V2GHalf, which will never discharge the transportation battery for grid services, will circumvent the warranty issue. In fact, the current SAE standard J1772, which specifies the electric coupler for electric vehicle charging, provides the communication via the Control Pilot to change the rate at which the battery are charged [SAE 2009]. Thus, this technology could be implemented in the near-term.

Furthermore, the results of this analysis provide a different perspective to the current discussion about the need and size of a public charging infrastructure. Currently, the American Recovery and Reinvestment Act of 2009 supports deployment of electric vehicles and the installation of a public charging infrastructure in specific locals. The key driver for public charging stations deployment has been to mitigate the range anxiety of pure electric vehicles by providing them recharge options to get back home, and to provide access to customers who live in high-density urban dwellings. It is too early to evaluate and determine the necessity of a public charging infrastructure for the early market adoption. Charging behavior analysis will need to be performed to provide the necessary insights into consumer behavior. In the absence of sufficient data to test the hypothesis for the need and size of a public charging infrastructure, a different perspective is offered on this discussion that may provide some insights into the value of public charging stations from an electric infrastructure point of view. If it is assumed that public or non-residential charging stations provide not only electric energy for the vehicle, but also provides the opportunity for the vehicle owner to offer grid services (V2GFull and/or V2GHalf), then the question for the “right” amount of public charging stations can, at least, be partially answered by the results discussed in section 6 “Work Charging Availability.”

As discussed above, there is a strong diminishing-return relationship with an increase of non-residential charging stations. Figure 18 and Figure 21 show that with the first 10% of non-residential charging stations, 80% of the grid balancing value can be provided. These results are strongly dependent on the driving behavior and where and how often the vehicle is used. Unless the driving behavior will change significantly over the next decades, or a larger population will work at home or assume part-time employments, which in turn influences the driving behavior, the 2001 Department of Transportation Household Travel Survey used in this analysis may still provide a reasonable first starting point for this discussion. This result suggests that as long as the need for addressing the range anxiety and the need for charging access is not substantiated, the argument for a large size of non-residential charging infrastructure from a grid service perspective does not hold. A ratio of 1:10 (public to residential charging stations) would enable electric vehicles to provide grid services over a 24-hour period and substantially enhance their value to the grid, compared to charging vehicles only at home.

With ongoing DOE electric vehicle monitoring efforts, more insights into the driving and charging behaviors are expected to be forthcoming. With new data, the needs and value of public charging stations can be further analyzed and investigated.

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A. Appendix

This appendix contains figures for additional simulations during the study. These results represented outcomes that did not significantly differ from the results presented, but are included for the sake of completion.

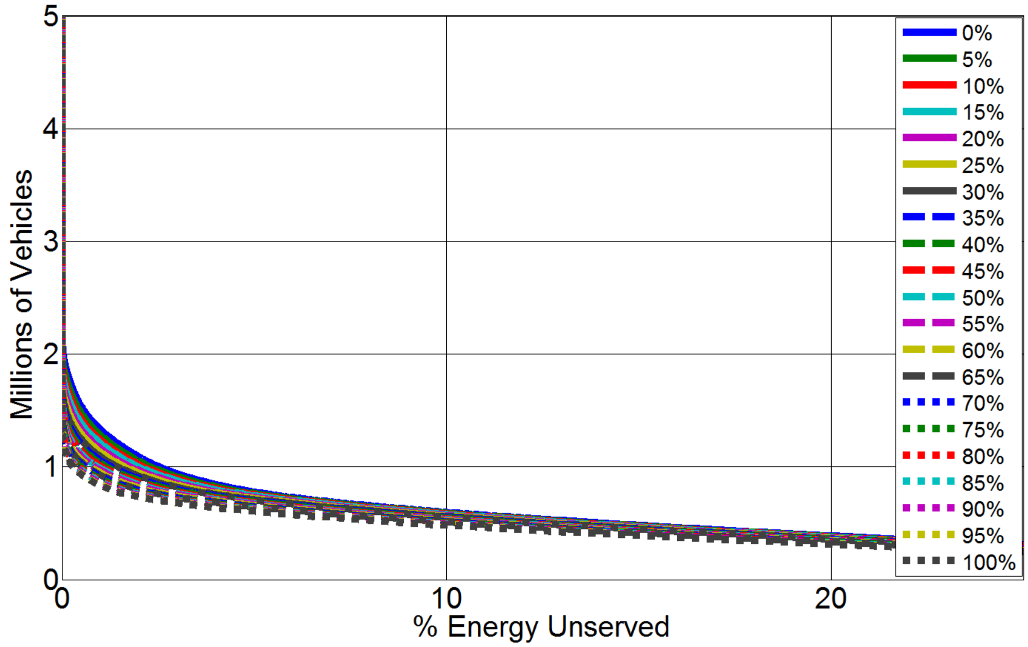

Figure A-1. Unserved energy percentage for V2GHalf vs. V2GFull Charging - PHEV-33

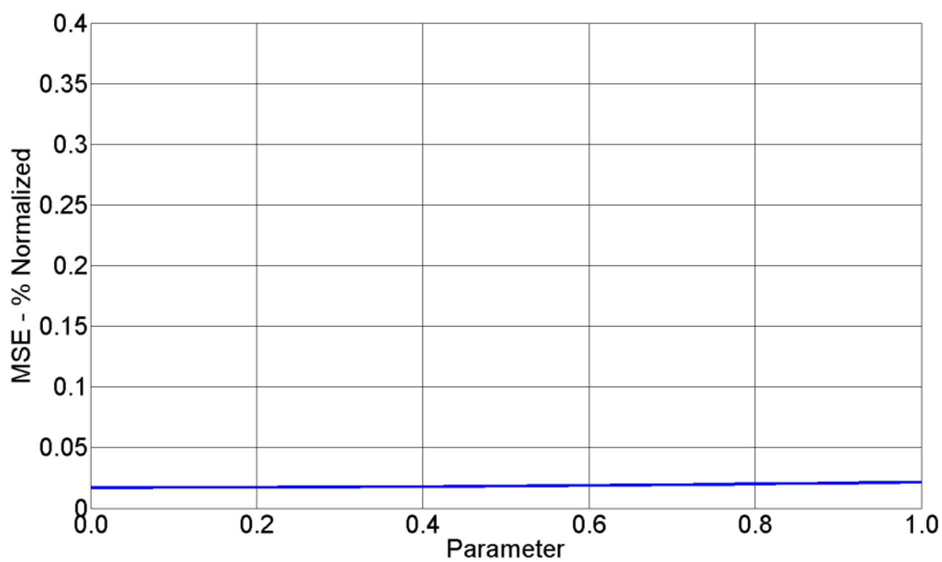

Figure A-2. MSE for V2GHalf vs. V2GFull Charging - PHEV-33

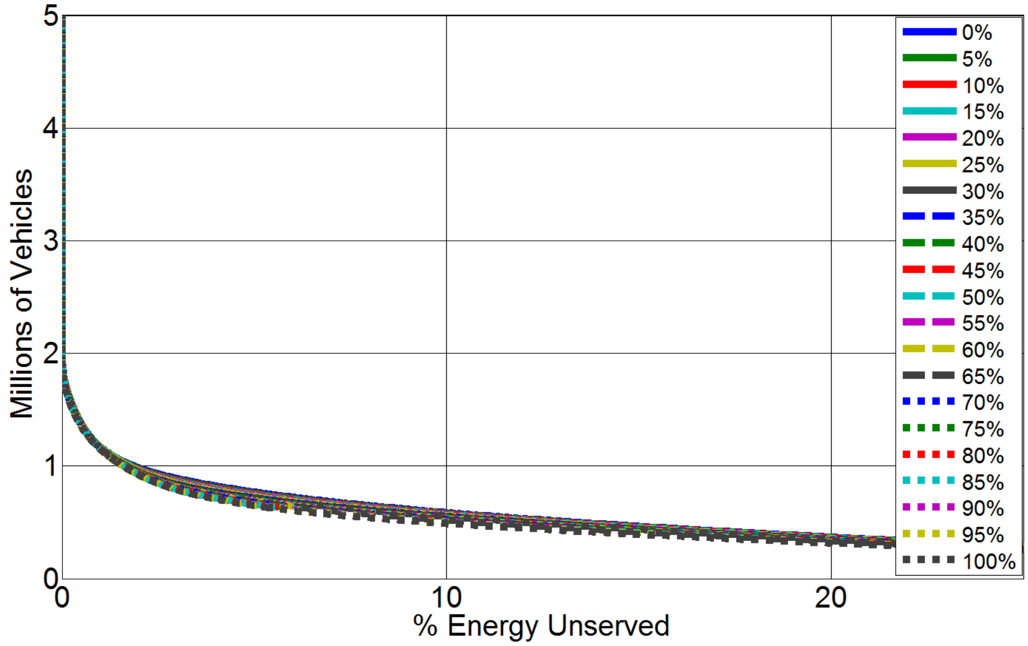

Figure A-3. Unserved energy percentage for home 240-Volt charging availability - V2GHalf only - PHEV-110

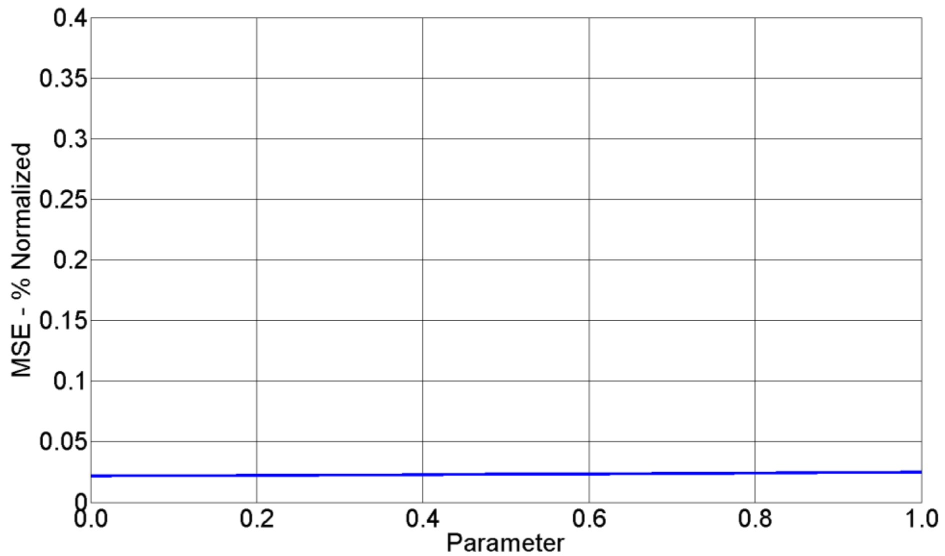

Figure A-4. MSE for home 240-Volt charging availability - V2GHalf only - PHEV-110

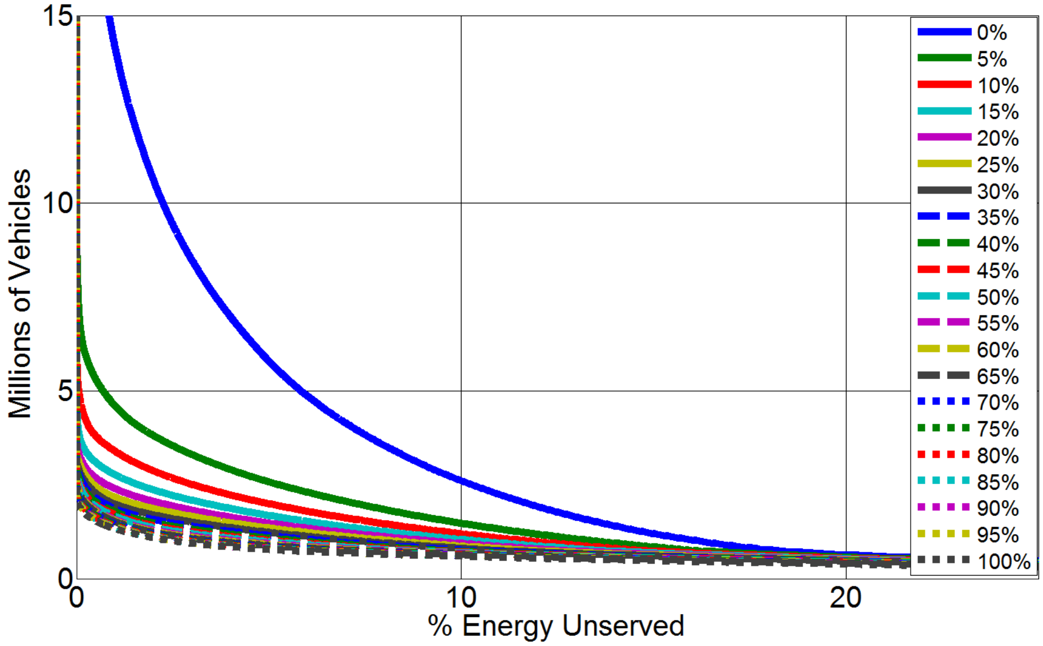

Figure A-5. Unserved energy percentage for work charging availability - V2GHalf only - PHEV-33

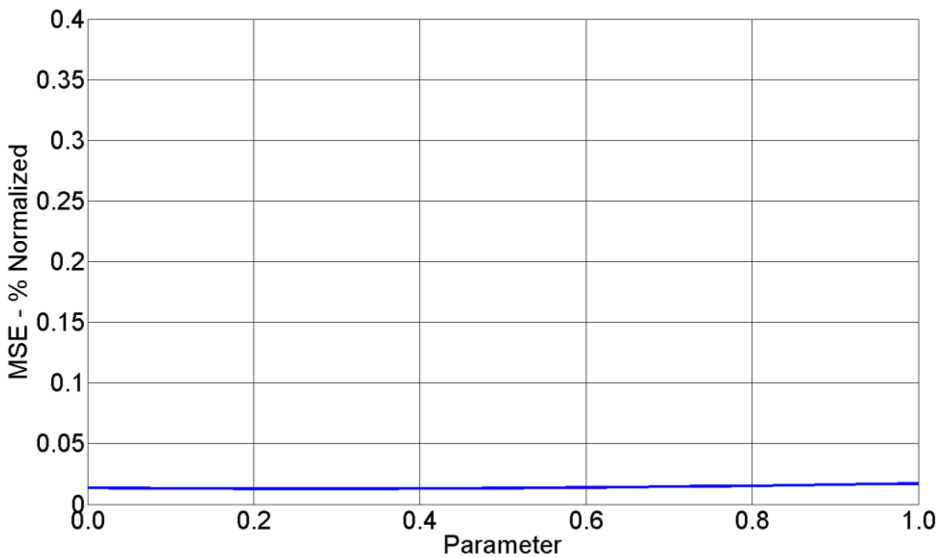

Figure A-6. MSE for work charging availability - V2GHalf only - PHEV-33

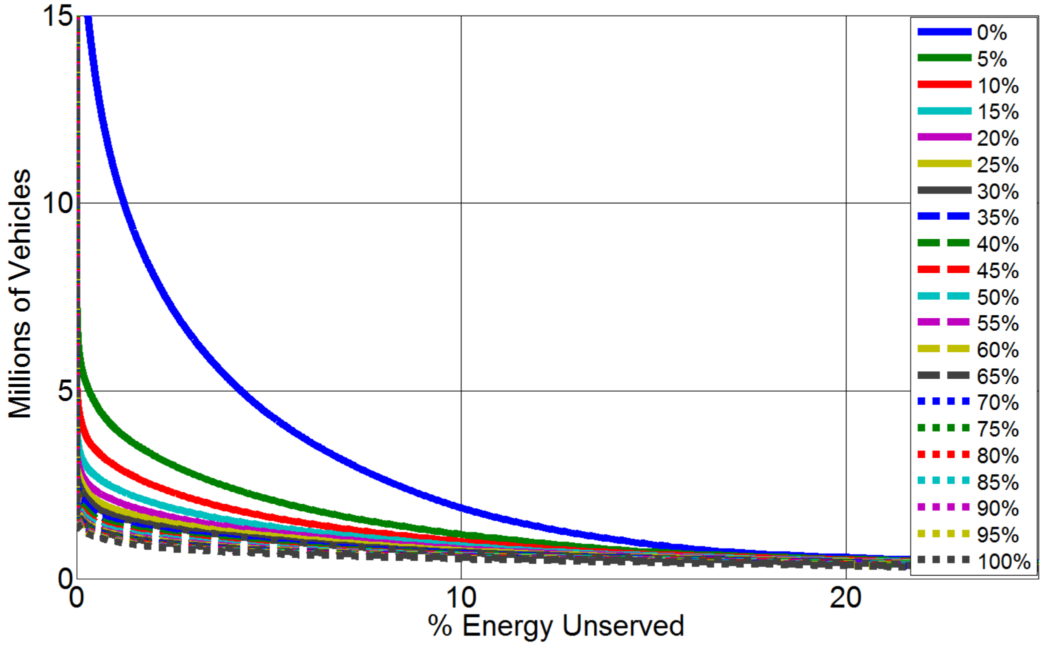

Figure A-7. Unserved energy percentage for work charging availability - V2GHalf and V2GFull - PHEV-33

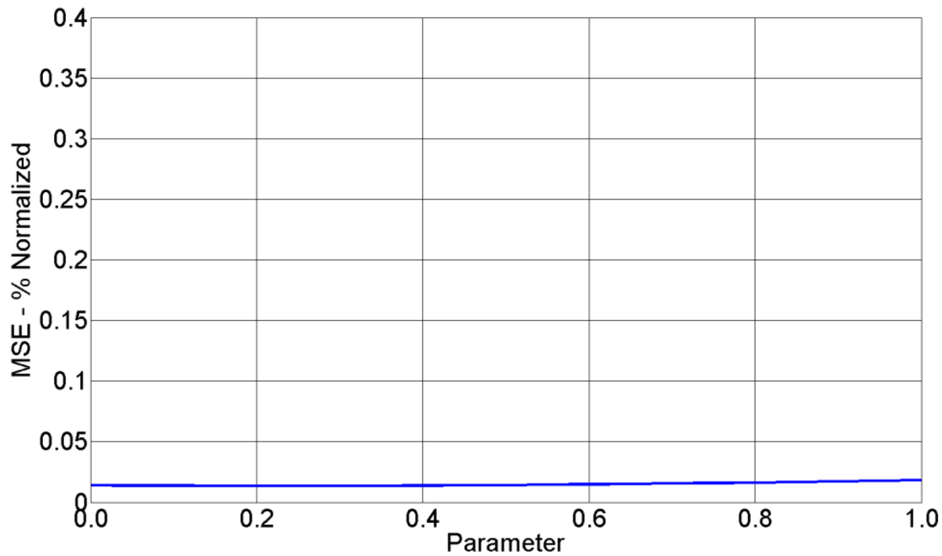

Figure A-8. MSE for work charging availability - V2GHalf and V2GFull - PHEV-33

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